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REVIEW

Dynamic Reliability Assessment of Heavy Vehicle Crossing a Prototype Bridge Deck by Using Simulation Technology and Health Monitoring Data

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ABSTRACT

Overloads of vehicle may cause damage to bridge structures, and how to assess the safety influence of heavy vehicles crossing the prototype bridge is one of the challenges. In this report, using a large amount of monitored data collected from the structural health monitoring system (SHMS) in service of the prototype bridge, of which the bridge type is large-span continuous rigid frame bridge, and adopting FEM simulation technique, we suggested a dynamic reliability assessment method in the report to assess the safety impact of heavy vehicles on the prototype bridge during operation. In the first place, by using the health monitored strain data, of which the selected monitored data time range is before the opening of traffic, the quasi dynamic reliability around the embedded sensor with no traffic load effects is obtained; then, with FEM technology, the FEM simulation model of one main span of the prototype bridge is built by using ANSYS software and then the dynamic reliability when the heavy vehicles crossing the prototype bridge corresponding to the middle-span web plate is comprehensively analyzed and discussed. At last, assuming that the main beam stress state change is in the stage of approximately linear elasticity under heavy vehicle loads impact, the authors got the impact level of heavy vehicles effects on the dynamic reliability of the prototype bridge. Based on a large number of field measured data, the dynamic reliability value calculated by our proposed methodology is more accurate. The method suggested in the paper can do good for not only the traffic management but also the damage analysis of bridges.

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1. Introduction

Heavy vehicle in many countries, especially in developing countries, is a widespread problem resulting in early damage of the bridge and brings in huge economic losses. Here, we take China as an example. By 2020, China's total expressway mileage is up to 161,000 km. Due to the reforms and opening up as well as the deepening of China's market economy, the states have heavily increased investment in infrastructure, bringing the transportation sector to a new stage. However, a variety of problems, such as increase in traffic, loads due to heavy-duty vehicles, increasing speed of the vehicles as well as increased carrying capacity, presents the transport sector with "high-volume, heavy and channel traffic" challenges. The increasing heavy trucks cause a cumulative growth in the standard axle load and lead to serious damage of the roads and bridges. Urban roads and bridges carrying these heavy transport regularly induce the bridge structures and its components to withstand large dynamic load and frequent load times. Although the stress level is far below the ultimate strength or yield limit of materials used in the bridges such as steel, concrete etc., it often causes sudden and unexpected destruction.

As for the impact of overweight vehicles on bridge safety, many scholars around the world have conducted extensive research. Kirkegaard P H et al. [1] considered the vehicle load dynamic amplification on minor highway bridges for evaluating the safety of the bridge structure load carrying capacity. Zhao Yu et al. [2] elaborate the evaluation steps, checking principles, checking methods and traffic management measures of the overweight vehicles passing through the bridge deck, which provides the way for evaluating the overweight vehicles passing through the bridge. Chang Hao et al. [3] take reinforcement measures seriously, of which the aim is to cooperate with overweight vehicles crossing the bridge, and resolutely put an end to all kinds of major accidents to ensure the smooth flow of the road. Jiang H et al. [4] established a bridge model with finite element software and the process that heavy vehicle pass through the bridge was simulated, and finally the safety margin of the bridge was evaluated on the basis of bearing capacity analysis. Na H S et al. [5] identified the dynamic characteristics with vehicle-impact loading and analyzed the behaviors of U-channel segmental concrete bridge (UCB) system. Yu Xiaofei [6] presents the harm of heavy vehicles to bridges, and puts forward relevant requirements for the problems needing attention in the management of heavy vehicles crossing bridges. Hu B X et al. [7] built a model of the random dense vehicle load of bridge structures and obtained three different degree dense vehicle loads by using the simulated model. Li Y H et al. [8] suggested a method for analyzing the probability of heavy vehicles with adopting the monitored strain data from a structural health monitoring system of a bridge. Tao Fuxian and Du shanpeng [9] introduce the evaluation method and checking calculation points of the bearing capacity of the bridge structure, and give the basis for the carrying capacity of the bridge structure under the overweight load, and introduce several engineering technology and management measures when the overweight vehicles cross the bridge. Wang K and Liu J [10] put forward the safety evaluation conclusion on the basis of bridge status and finite element calculation which ensured the overweight vehicle to cross hollow plate girder bridge safety. Liu Jing and Cao Xintao [11] check the bearing capacity of the bridge, and put forward the corresponding bridge management measures, so as to reduce the harm of overweight vehicles to the highway bridge and improve the bearing capacity of the bridge. W. Han et al. [12] presented a methodology for assessing the safety of prestressed concrete box-beam bridges with considering customized transport vehicle load effects. As for large number of bridge collapse accidents due to heavy truck. Zhu Songye et al. [13] suggested a vehicle-bridge coupled vibration model of a rigid-frame bridge for evaluating bridge structure safety under practical traffic loads effects. Evgeny A. Lugovtsev [14] implemented programs with an experimental and analytical method for assessing the technical condition of road bridges for reliability, and revealed the features, conditions of application, positive and negative aspects of each version of the program.

In short, researchers in the word wide still lack data to assist doing safety impact assessment of heavy vehicle load effects for bridge structures. The present study lacks effective support from field measured data. Consequently, by using large amount of strain monitoring data and ANSYS software, a method is suggested to assess the safety impact of heavy vehicle on the prototype bridge in this paper. Based on large amount of in-situ measured data, the calculated value got by our suggested method is closer to the bridge structure actual situation. We firstly suggested a calculation method for the dynamic reliability calculation of the abnormal load of a type overweight vehicle, and the method can also be extended to do security evaluation for other abnormal loads. The method is very useful for of the bridge traffic management, and hence can effectively reduce the damage of bridge structures under heavy vehicle load effects.

2. Brief Introduction of the Prototype Bridge

2.1 Structural Health Monitoring System of the Prototype Bridge

The superstructure of the prototype bridge main beam is a continuous box-beam system with a total of eight main piers and 7 main spans. The first span is 145.4 m long and the sixth span is 87 m long, and the 4 center spans are all 144 m long. The cross section of box girder is a single-box and single-chamber. The width of box girder top plate is 12.5 and the base plate width of is 6.8 m. The bridge deck transverse slope is 2.0% and the bridge deck longitudinal slope is 0.15%. The heights of the main beam cross sections change from 8 m to 2.8 m according to 1.6 order power parabola from the supporting base to the mid-span. The thickness of the main beam base plate varies from 1 m to 0.32 m and thickness of the main beam web plate varies 0.9 m to 0.45 m. The main beam is fully prestressed concrete structure with vertical, horizontal and longitudinal prestressed arrangement, and the prestressed tendons are $15\Phi^{j}15.24\,\mathrm{mm}$ steel strand with the strength: $R_y^b = 1860\,\mathrm{MPa}$, $2\Phi^{j}12.7\,\mathrm{mm}$ steel strand with the strength: $R_y^b = 1395\,\mathrm{MPa}$ and high strength rebar respectively.

The monitoring points of the SHM in each cross section of the main beam locate near piers, in mid-span and in 1/4 span, with total 20 sections. Among them, there are 8 cantilever end sections, 8 L/4 span sections, and 4 L/2 span sections. The strain variety sensor material object (JMZX-215 type) is shown in Figure 1, which is string type strain gauge. The section locations can be seen in Figure 2. The sensor embedded locations in each section can be seen in Figure 3 with unique given numbers. With the given name of cross section and number, a sensor in the SHMS can be located in the girder uniquely, such as a sensor is named 3-4MID-1, which means that it locates in the top plate center of the mid-span cross-section between pier 3# and pier 4#. The sensors manufacturer is CHANGSHA KINGMACH HIGHTECHNICS CO., LTD [15]. With the given name of cross section and number, a sensor in the SHMS can be located in the girder uniquely. The sensor measuring time interval is 1 hour. The strain gauge parameters are shown in Table 1. The health monitoring system is still operating normally at present, and a large amount of strain monitored data have been obtained.

Table 1. Parameters of the strain gauge

Name	Range	Sensitivity	Gauge length	Remarks
Intelligent digital vibrating strain gauge	±1500 $\mu\varepsilon$	1 $\mu\varepsilon$	157 mm	Strain gauge embedded in concrete

Figure 1. Picture of the JMZX-215 strain gauge

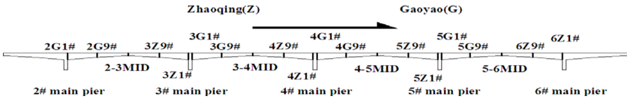


Figure 2. Cross section locations of the embedded sensors of SHMS

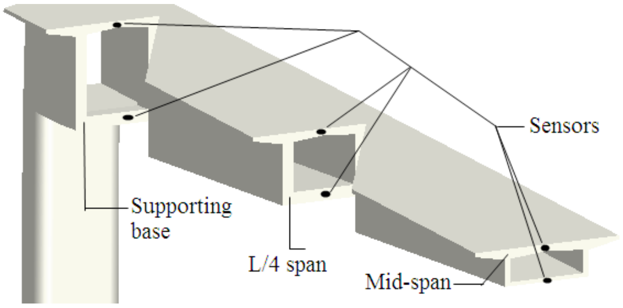


Figure 3. Position of the embedded sensors in half-span of the prototype bridge

2.2 The Acquired Strain Data of the Bridge SHMS

In this article, the data acquired from the sensors 3G1H-1, 3-4MID-1, 4Z9H-1 and 3-4MID-2 are used by us as examples to display the outline of the monitoring data, and the chosen time range is from March 2006 to April 2010. The pre-processed method that how to transform the initial data into strain data can be seen in the papers [16,17]. Figure 4 shows the profile of the original data after several pre-processed steps.

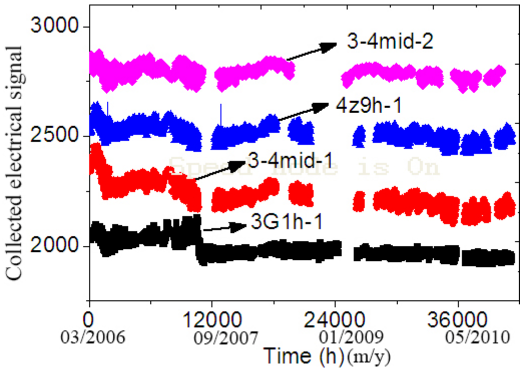


Figure 4. The graph of the monitored data after pre-processed steps

3. Main Idea of Calculation of Initial Quasi Dynamic Reliability

3.1 The Fundamental Theory of First Order Second Moment Method

In this article, the first order second moment method is adopted to calculate structural members' safety index β, and its reliability index β calculation expression can be written as follows:

$$\beta = -\Phi^{-1}(P_f) = (\mu_R - \mu_S)/(\sigma_R^2 + \sigma_S^2)^{1/2} \tag{1}$$

where Φ^{-1} is the inverse function of the standard normal distribution; μ_R and μ_S are the mean of the resistance and load effects respectively; σ_R and σ_S are the standard deviation of the resistance and load effects respectively. The concrete strength probability distribution function basically obey Gaussian distribution and can be taken as the probability density function of the resistance R.

3.2 The Definition of Quasi Dynamic Reliability

As the concrete compressive and tensile strength parameters are measured by testing machine at a certain strain rate, then, the concrete compressive and tensile strength are called by the name of quasi dynamic compressive strength and quasi dynamic tensile strength. The mean and standard deviation values of the concrete quasi dynamic compressive and tensile strength respectively with 28 days curing are shown in Table 2.

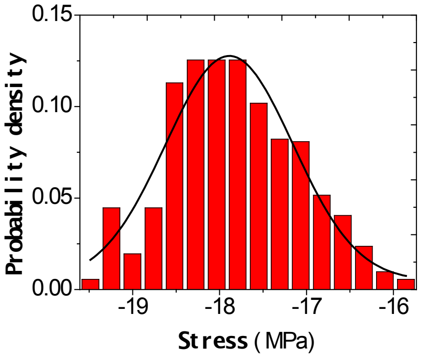
Table 2. The quasi dynamic parameters of concrete compressive and tensile strength used in the prototype bridge

Strength	**Mean (units: MPa)**	**Standard deviation (units: MPa)**
compressive	55.12	6.063
tensile	3.2783	0.361

In the meanwhile, as the load effects σ_S (acquired by SHM) includes the quasi dynamic load effects, such as temperature load effect, vehicle load effects etc., so, we name the safety index the initial quasi dynamic reliability β_q.

3.3 The Calculation of the Initial Quasi Dynamic Reliability β_q

As for the prestress loss and concrete shrinkage and creep etc., the load effects σ_S distribution gradually close to concrete tensile strength distribution with time, therefore, we calculate the initial quasi dynamic reliability β_q by using the quasi dynamic tensile strength distribution as the the resistance σ_R. The method of quasi dynamic load effects σ_S transferred from the monitored data and initial quasi dynamic reliability β_q calculation step both can be seen in the papers [18,19]. Figure 5 illustrates the quasi dynamic load effects σ_S distribution. In the report, the data collected from the sensor 2-3MID-2, which is embedded in the mid-span web plate between the main pier 2# and main pier 3#, are taken as examples, and the selected time range is from March 2006 to October 2006. During March 2006 to October 2006, the bridge has just begun to enter into service, which reflects the quasi dynamic reliability state of the bridge at the beginning of operation. Based on Equation (1), the initial quasi dynamic reliability β_q value is got, seen in Table 3. Since the selected monitored data time range is before the opening of traffic, and so the traffic load effect is not included in the monitored data.



(2-3MID-2) 2006.05 ～ 2006.10

Figure 5. The graph of quasi dynamic load effects σ_S distribution and Gaussian distribution fitting

Table 3. The initial quasi dynamic reliability β_q value in mid-span web plate between main pier#2 and main pier#3

Sensor number	**2-3MID-2**
The initial quasi dynamic reliability β_q value	10.7903

4. The Building of Simulation Model for Heavy Vehicle Passing through the Bridge

4.1 Building of the FEM Model

In order to obtain the dynamic load effects induced by heavy vehicles, FEM technology is used to simulate heavy vehicles passing through the bridge. Here, the sub-model technology will be used to learn the local responses in the bridge [20,21], which helps to simplify the analysis model and get enough analysis accuracy. A FEM sub-model of the prototype bridge is set up including the girder between the main pier 2# and the main pier 3# (shown in Figure 6). In this model, a 3D element (solid 45 element) with the shortest length 0.25 m is used to simulate concrete, and there are 37,388 elements and 57600 nodes in the sub-mode. The boundary condition of the FEM model is set as consolidation.

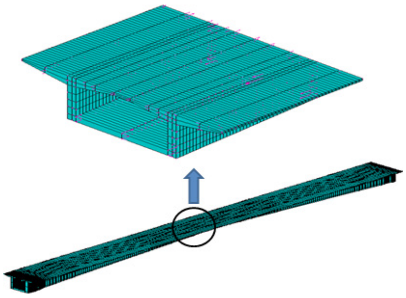


Figure 6. Schematic and mesh mode of FEM sub-model

4.2 Calibration of the Reliability of the Simulation Model

For the sake of checking the reliability of the FEM model, we have done a calibration work on a loading capacity test of the bridge before the bridge came into service. On the test, utmost ten QC-20 main vehicles (a truck loading model with the weight 300 kN defined in a Chinese Specification JTG D60-04 [22]) were used, and they were divided into four loading levels: 900 kN, 1500 kN, 2400 kN, 3000 kN. At present, we have only the static loading test data for the calibration of the FEM model. Figure 7 shows the loading distribution of each loading level, where first loading level included trucks with "①" and second loading level included trucks with "①" and "②", and so on. Figure 8 illustrates the comparison between the measured results and FEM results at the position sensor 2-3MID-2 located, and the two results have a good agreement, and the errors between numerical and tested strains of the four data points shown in Figure 8 are 18.4%, 4.92%, 14.6%, 7.9%, which means that the built FEM model is reliable.

4.3 The Simulation Process

In this paper, the key is to design a reasonable load in FEM model to represent the heavy vehicle. Here we introduce one kind of vehicle loads with four kinds of speeds: A QC-20 heavy truck with about double standard load. The alxe load distribution is shown in Figure 9, and such load will "move" along the span with speed 10 m/s, 20 m/s to learn the response strength around the sensor 2-3MID-2 at the mid-span.

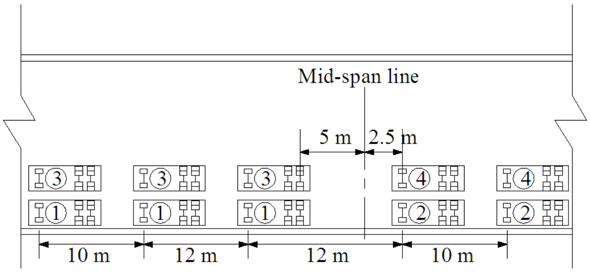


Figure 7. Loading Scheme of the loading capacity test

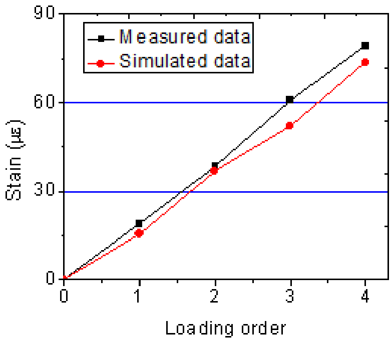


Figure 8. Comparison between the simulated data and the monitored data (Corresponding to the sensor 2-3MID-2)

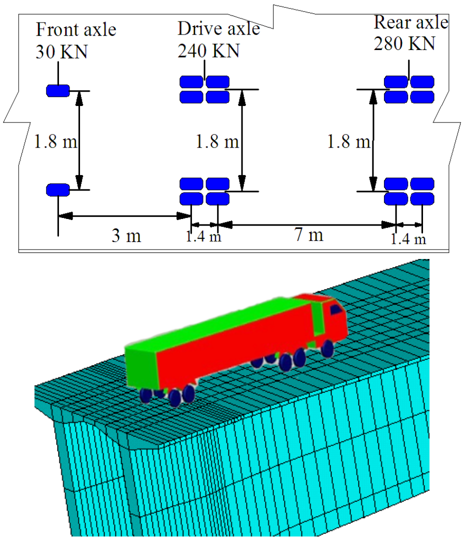


Figure 9. Load's distribution of QC-20 heavy vehicle and moving diagram

Vehicle loads also have impact effect on bridges. Hwang and Nowak [22] developed models for trucks, road surface (roughness) and the bridge, which dealt with the analysis of dynamic loads in bridges, and found that the simulated deflections indicate that the dynamic component is not correlated with the static component, and also found that the dynamic loads are lower for heavier truck and the dynamic loads for two trucks are lower than for single trucks. According to a Chinese Specification JTG D60-04 [23], the impact coefficient of vehicle load takes the value 0.081. By considering the four vehicle loading effects and the dynamic properties, Stress values generated under vehicles passing through the girder in the above case, at the sensor 2-3MID-2 position, can be seen in Figure 10. After we got the stress data, we then do normal distribution statistical analysis, which can be seen from Figure 10, and we can find that the stress data are basically normally distributed. Therefore, we deal with the stress statistical data with Gaussian distribution fitting, seen in Figure 10.

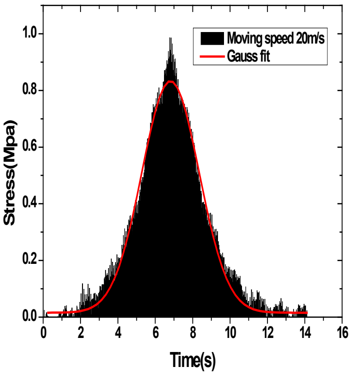


Figure 10. Gaussian distribution fitting of the stress distribution statistics

5. Results and Discussion

5.1 Some Properties of Normal Distribution

The normal distribution has some very important characteristics, such as: if $X \sim N(\mu_X, \sigma_X^2)$ and $Y \sim N(\mu_Y, \sigma_Y^2)$ are statistically independent normal random variables, and also the sum of them satisfies the normal distribution, and can be written as the following formula:

$$X + Y \sim N(\mu_X + \mu_Y, \sigma_X^2 + \sigma_Y^2) \tag{2}$$

5.2 Formula Derivation of Heavy Vehicle Load Effects Impact on Bridge Structure Reliability

According to the stress-strain characteristics of high-strength concrete specified in the standard "code for design of concrete structures" [24], we assume that the main beam stress state change is in the stage of approximately linear elasticity under heavy vehicle loads impact in this article. Hence, the heavy vehicle load effects and the quasi load effects transformed from the monitored data are statistically independent random variables, through formulas (1) and (2), and the initial quasi dynamic reliability calculation formula with considering the influence of heavy vehicle loads can be derived as follows:

$$\beta_{qc} = \frac{\mu_R - (\mu_M + \mu_{qc})}{\sqrt{\sigma_R^2 + \sigma_M^2 + \sigma_{qc}^2}} \tag{3}$$

where, β_{qc} is the initial quasi dynamic dynamic reliability index considering heavy vehicle effects; μ_R is the mean of the resistance, and μ_M is the mean of quasi load effects transformed from the SHM; σ_R is the standard deviation of the resistance, and σ_M is the standard deviation of the quasi load effects transformed from the SHM; μ_{qc} is the mean of heavy vehicle effects, and σ_{qc} is the standard deviation of the heavy vehicle effects.

By Gaussian distribution fitting of the stress distribution statistics, seen in Figure 10, the values of μ_{qc} and σ_{qc} were obtained, and can been seen in Table 4.

Table 4. The values of μ_{qc} and σ_{qc} corresponding to the sensor 2-3MID-2 embedded in mid-span web plate

Speed	10m/s	20m/s
μ_{qc} (MPa)	0.238	0.238
σ_{qc}^2 (MPa)	0.0797	0.0801

With the data in Table 1 and Table 3, we calculated the dynamic reliability index values β_{qc} with the Equation (3), and then we got the values which are shown in Table 5.

Table 5. The values β_{qc} corresponding to the sensor 2-3MID-2 position embedded in mid-span web plate

Speed	10m/s	20m/s
β_{qc}	10.354	10.640

By comprehensive analysis of the data shown in Table 2 and Table 4, the impact level of heavy vehicle loads on dynamic reliability of the prototype bridge is obtained, and in the paper we name it $\Delta\beta_{qc}$, of which the values can be seen in Table 6.

Table 6. The values $\Delta\beta_{qc}$ caused by heavy vehicle loads

Speed	10m/s	20m/s
$\Delta\beta_{qc}$	0.437	0.151

It can be seen from Figure 9 that the variation range of the stress induced by heavy vehicle is about 1 MPa in the mid-span web plate of the prototype bridge, and it is in a safe state, because the change range is in the bearing capacity limit and the pressure safety reserve of the concrete materials during the bridge in the early stage of service. According to the above results, under a heavy vehicle intensity influence，the range of variation of the quasi dynamic reliability $\Delta\beta_{qc}$ is about 0.15-0.44 in the mid-span web plate corresponding to the sensor 2-3MID-2 position, of which the meaning is that heavy vehicle load effects have limited impact on bridge safety.

6. Conclusions

As for the difficulties of safety evaluation of load effects of the heavy vehicle for bridges, combine with the large amount of monitored strain data acquired from the SHMS of the prototype bridge and simulation technology, a evaluation method is put forward for assessing the dynamic reliability of this type bridge under heavy vehicle load effects influence in this paper, and the main conclusions are:

1) Assuming that the main beam stress state change is in the stage of approximately linear elasticity under heavy vehicle loads impact, a methodology is presented for the calculation of dynamic reliability of the prototype bridge with considering heavy vehicle load effects, and we found that the heavy vehicle load effects have limited impact on bridge safety. Also, we found that the range of stress change induced by heavy vehicle is small.

2) The statistical analysis of the simulated a type heavy vehicle load effects indicates that they basically obey Gaussian distribution, and hence we can use the first order second moment method to assess the heavy vehicle load effects safety influence on bridge structures.

3) The next research project should pay key attention to the bridge aging, the bridge material strength degradation, shrinkage and creep of concrete etc., and then study the reliability of bridge structures taking into account heavy vehicle load effects. When the prototype bridge served for a long time, conducting the analysis whether the safety reserve of the bridge meets the heavy vehicle load effects safety requirements or not is quite necessary. In the meanwhile, the next step research plan should also focus on finding out the difference between this study’s quasi-result and the actual result.

The means suggested in the paper can provide basis and direction for the safety evaluating of bridge structures encountering other abnormal events.

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Conflict of Interest

There is no conflict of interest.

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