# Research on monitoring technology of underground diaphragm wall construction of small and medium-sized circular shafts based on artificial intelligence

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## ABSTRACT

Circular shaft diaphragm walls are mostly circular, but the existing theories are mostly based on rectangular or planar structures, which lack support for the design and construction monitoring of circular shafts. In this paper, based on actual cases, the parameters such as water-soil pressure, wall strain and soil displacement behind the wall during the construction of circular shaft diaphragm walls are analyzed to explore their mechanical behavior and force characteristics. The results show that the circular vertical shaft diaphragm wall has unique mechanical behavior and force characteristics, which are different from the traditional theory. The earth pressure is maximum at the depth of 4 m, which is far more than the value of Rankine's theory; the ground stacking load has a significant effect on the earth pressure; the wall strain and the soil displacement behind the wall are small, which shows a good self-stabilizing effect. The conclusions of this paper are of great significance to optimize the construction and improve the safety, and provide reference for similar projects.

**Keywords:** Circular shaft, diaphragm wall, informationized monitoring, stress analysis

## 1. INTRODUCTION

With the rapid development of China's long-distance oil and gas pipeline construction, oil and gas pipeline construction needs to cross the complex geological environment, commonly used shield, directional drilling, large excavation, crossing and other methods[1]. Shield method is preferred, but it is affected by the construction of vertical shafts and prone to accidents. Diaphragm walls have several advantages and are commonly used in circular and square shapes[2]. Circular diaphragm walls are commonly used for small and medium-sized shafts, but their construction monitoring techniques are complicated. Therefore, it is crucial to study the construction monitoring technology of polygonal approximate circular diaphragm walls[3-5]. In recent years, the monitoring scope of underground engineering has been expanded[6], the monitoring means are intelligentized[7], and the sensor technology is improved. Online monitoring technology realizes real-time acquisition and analysis, and improves construction monitoring efficiency[8]. However, the monitoring of polygonal near-circular diaphragm wall still has problems, such as sensor arrangement, data processing[9,10].

The monitoring data are analyzed in various ways, but the theory is often different from the reality, and the numerical methods are also limited[11-13]. Therefore, in this paper, based on the construction monitoring data of polygonal approximate circular diaphragm wall, the changes of various parameters during the construction of the shaft are analyzed in depth. The conclusion of the study is of great significance to optimize the construction process of the shaft and improve the construction safety, and provides a reference for similar projects.

## 2. PROJECT OVERVIEW

Guangdong Natural Gas Pipeline Network Phase II Nan Tanhai Shield Project is located in Huicheng Town, Jiangmen City, and the starting shaft is located in Hebei Village, Xinhui District, Jiangmen City, traversing a variety of strata. The shaft adopts underground diaphragm wall to stop the water curtain, and the internal concrete lining is poured. The diaphragm wall has a depth of 20 m, a thickness of 0.8 m, and consists of 10 internal "eight" shaped groove sections. The inner lining is a circular structure with a diameter of 14 m, a depth of 18.98 m, a wall thickness of 0.8 m, and three ring

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beams for reinforcement. The project is divided into ten polygonal slots according to the design, including five slots in Phase I and Phase II.

# 3. ESTABLISHMENT OF INFORMATIZATION MONITORING SYSTEM

During the excavation of the circular shaft pit, monitoring data, theoretical and numerical inverse analysis tools are used to predict the displacement and deformation of the diaphragm wall, to grasp the displacement of the enclosing structure, to forecast construction problems, to determine the causes of structural dislocation, and to informatively guide construction to prevent excessive deformation and ensure structural safety. Figure 1 demonstrates the informatized construction monitoring process, combining construction monitoring, mechanical calculation and empirical methods, selecting parameters based on preliminary geological investigation and pre-design, and then adjusting the construction process and parameters according to the monitoring information to adapt to the stability of the strata, the mechanical and working status of the support system and the impact on the surrounding environment. According to the actual monitoring data, comparing the original design scheme, the original design can be tested and optimization suggestions can be made to develop the design theory, so as to achieve a completely meaningful information construction monitoring. The main contents of circular shaft diaphragm wall monitoring include the following aspects:

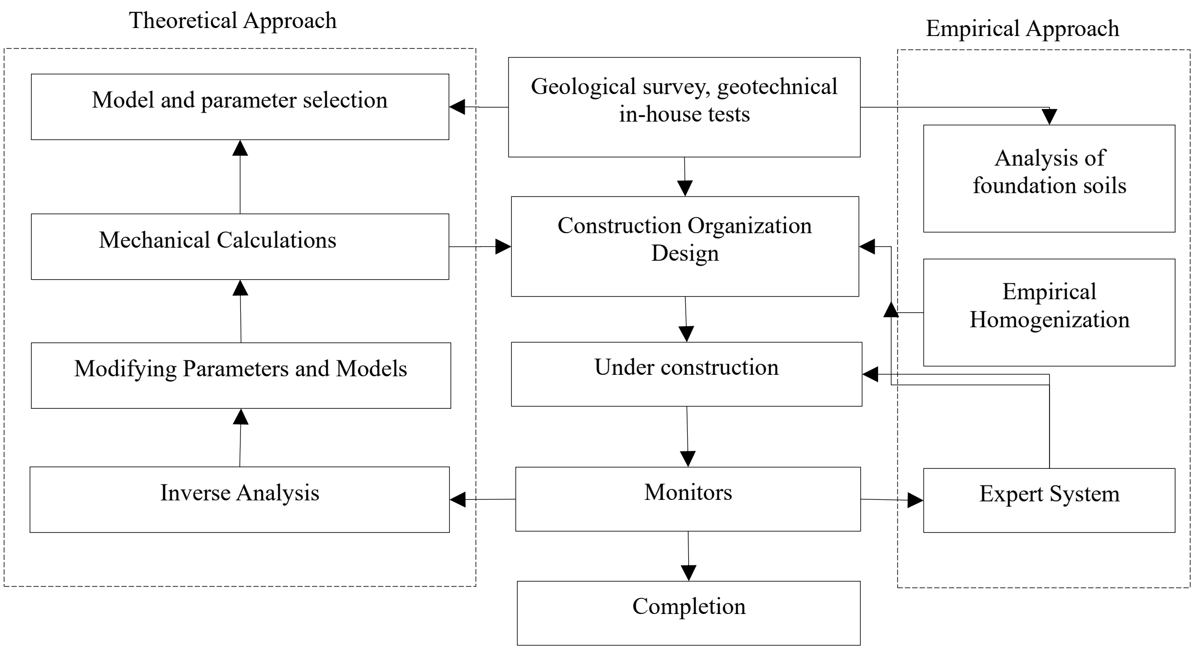


Figure 1. Construction monitoring and informationized construction process.

## 3.1 Informatized monitoring of deformation of circular shaft enclosures

The support structure of this circular shaft project is a diaphragm wall without internal support in the form of “two-in-one”, with a roof ring beam at the top, which is supported by its own arch effect. When calculating, the support can be regarded as an elastic foundation beam, and the force arch effect is equivalent to virtual support. Inside the diaphragm wall, the inclined pipe is buried to monitor the deformation, and the soil pressure box is buried at multiple depths on the outside to monitor the soil pressure value. According to the elastic mechanics plane strain problem, the equivalent support elastic modulus E1 is derived to predict the displacement of the diaphragm wall after shaft excavation[14].

$$E_1 = -\frac{a+b}{A[4\frac{1+v}{a+b}\frac{a^2b^2}{b^2-a^2}+(1-2v)(1+v)\frac{b^2}{b-a}]}E$$

where *E* is the modulus of elasticity of the circular support material; *v* is the Poisson’s ratio; *a* and *b* are the inner and outer diameters of the enclosure; and *A* is the cross-sectional area of the support.

The equivalent support modulus of elasticity is used as an elastic foundation beam input parameter to calculate the internal forces and displacements of the circular support structure according to the elastic foundation beam method. Calculate without considering the inner lining, according to the principle of soil and water separation. The circular support structure is discretized into virtual supports, and the supports are encrypted by adding one for every 1-2 m of excavation. This can predict the size of continuous wall displacement at the depth of excavation, and obtain the difference between the earth pressure calculation and the actual value, judge the balance state of the soil behind the wall, and further judge the reinforcement requirements of the support structure.

### 3.2 Informative monitoring of the seepage field outside the diaphragm wall of a circular shaft

When designing polygonal approximate circular diaphragm walls according to the code method, the group found that the reinforcement is closely related to the groundwater level and even plays a decisive role. However, the seepage field was constantly changing during the construction of the diaphragm wall. The pore water pressure test showed that the super void water pressure endured by the wall structure is much smaller than the static water pressure, and the traditional design is conservative. The change of seepage field outside the wall has an important effect on the force of the wall structure, and it is necessary to monitor the seepage field of the soil outside the wall of the shaft to verify the scientificity of the design method.

### 3.3 Informatization monitoring of stress-strain of concrete and steel reinforcement of continuous wall of circular shaft

The stresses borne by polygonal approximate circular diaphragm wall include the strain and stress of concrete and steel reinforcement in the tension and compression zones of the wall. Its structural design still has many theoretical problems to be solved. Real-time monitoring of these two aspects of the specific project can accumulate first-hand information, which is of great significance for solving the design problems of circular underground continuous structures, and also helps to verify the newly proposed theory of underground continuous wall structural design.

### 3.4 Data acquisition and transmission system based on wireless network transmission technology

Engineering monitoring means and data acquisition, processing and transmission technologies have matured. With the development of sensor and wireless network technology, engineering monitoring realizes online automatic monitoring, processing, wireless transmission[15,16], etc. 5G network makes large-capacity data transmission more convenient, reduces data loss, and can transmit on-site videos and pictures. This not only facilitates on-site personnel to access monitoring data, but also allows remote management and technical layer personnel to access monitoring data and make judgment in real time. This type of monitoring improves efficiency and accuracy and is the mainstream of the future. As the accuracy and life span of sensors increase, data acquisition and transmission systems become more practical[17,18].

## 4. PROCESSING AND ANALYSIS OF MONITORING DATA

### 4.1 Longitudinal rebar stress monitoring data analysis

Exploring the stress time change relationship of longitudinal reinforcement in the compression zone and tension zone along the depth respectively, Figures 2 and 3 show that: the pressure on the reinforcement in the tension zone changes greatly along the depth, and there is a strong nonlinearity, and the pressure change along the depth of the “s” type. Therefore, small and medium-sized circular diaphragm walls are subjected to uniform force without obvious stress concentration, and the distribution of reinforcement cage is relatively uniform. However, in order to ensure the stability, high reinforcement rate is often used, but there are some problems: high reinforcement rate cannot give full play to the tensile properties of steel, and may reduce the compressive properties of concrete. Therefore, it is necessary to study the reinforcement rate in depth, and combine with the actual project to carry out a reasonable design.

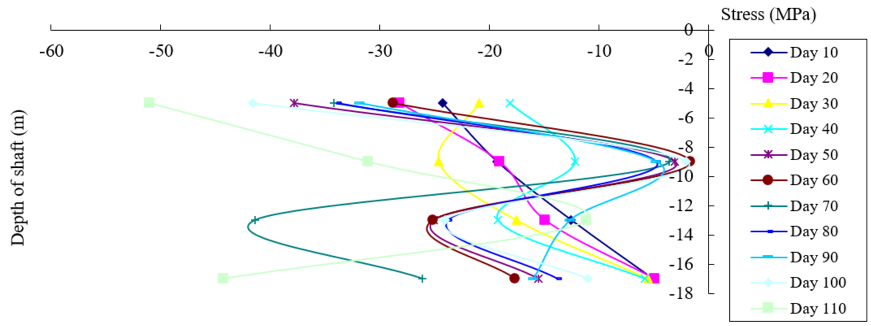


Figure 2. Stress variation of reinforcement along depth in tension zone.

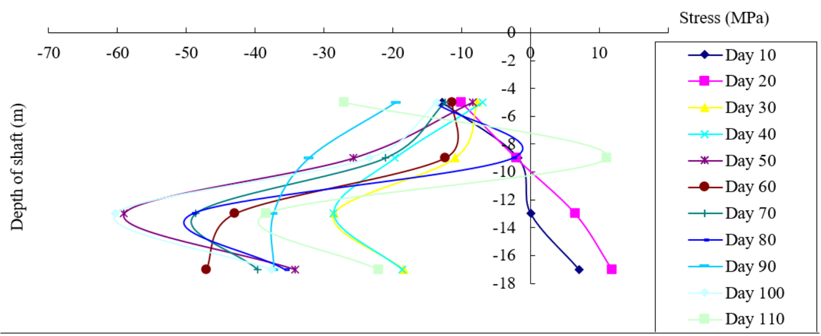


Figure 3. Variation of reinforcement stress along depth in the compression zone.

### 4.2 Transverse rebar stress monitoring data analysis

As can be seen from Figures 4-6, the transverse reinforcement force varied with depth, and among the three field-installed transverse reinforcement gauges, the 6 m and 12 m were subjected to pressure, and the 9 m was subjected to a smaller tensile force, which may be related to the local special conditions. During the construction, the force at each depth was basically stable, with occasional sudden changes due to the influence of ground pile load. This shows that the small and medium-sized circular diaphragm wall is significantly pressurized in the ring direction; in addition, most of the longitudinal and transverse reinforcement is pressurized, and the stresses they are subjected to are small most of the time, which indicates that their loading effects are not fully realized. The planar earth pressure theory of Rankine theory is the lower-limit solution and Coulomb theory is the upper-limit solution, both of which are too aggressive or conservative in design. The earth pressure calculation of small and medium-sized circular diaphragm walls should be between the two. Adopting the three calculation methods for load design, combined with the structural requirements, scientific and reasonable reinforcement is crucial to improve the design level.

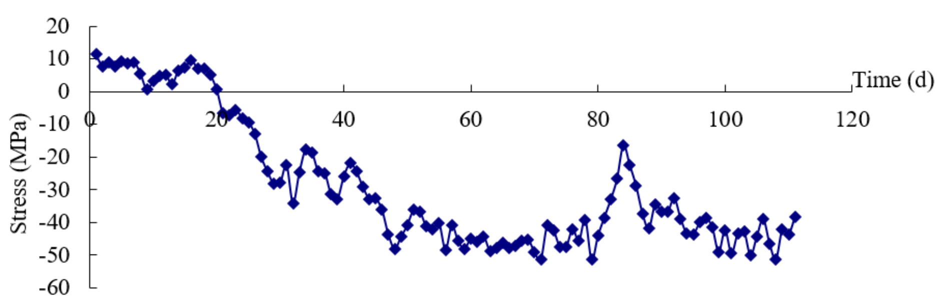


Figure 4. Stress time variation relationship of transverse reinforcement at 6 m depth in compression zone.

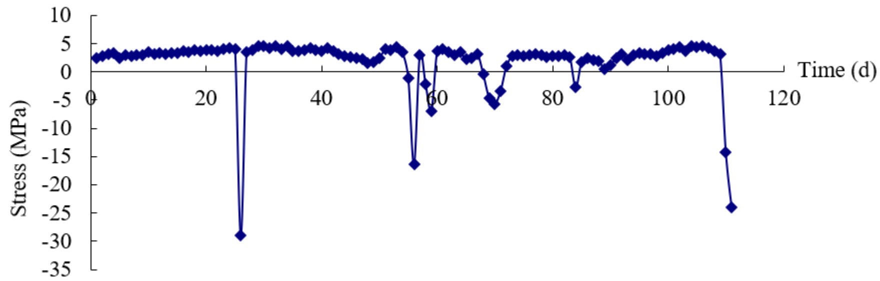


Figure 5. Stress time variation relationship of transverse reinforcement at 9 m depth in compression zone.

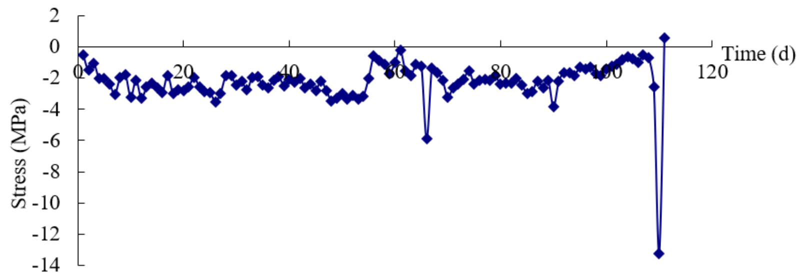


Figure 6. Stress time variation relationship of transverse reinforcement at 12 m depth in compression zone.

### 4.3 Analysis of concrete strain monitoring data

In order to understand the strain of concrete in the compression zone, concrete strain gauges were installed for measurement. From the curve changes and construction conditions, it can be seen that the concrete strain changed significantly during the construction process. Due to the online data collection, there are jumps in the daily data, but the overall strain is very small, mostly within a few hundred millimeters, almost negligible. Both compressive and tensile properties are distributed, probably related to the sensor sensitivity. With the change of depth, the concrete strain changes more obviously, showing irregularity, similar to the “s” shape, as shown in Figure 7.

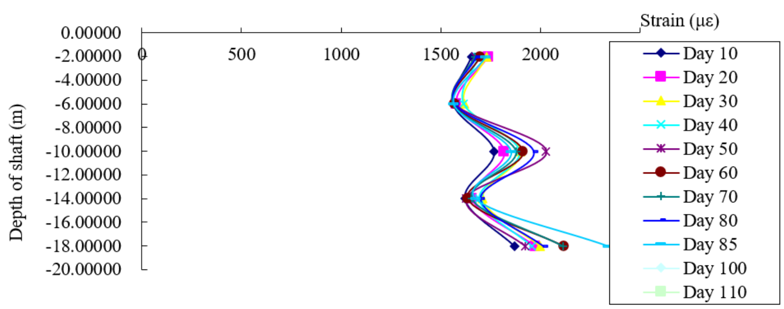


Figure 7. Variation curve of concrete strain along depth in the pressurized area B1-B5# of the start wells.

### 4.4 Pore water pressure construction monitoring data

To study the vertical shaft diaphragm wall, several pore water manometers were set up to monitor the pore water pressure around the shaft. The monitoring data were used to analyze the changes in the groundwater seepage field during the excavation of the shaft. The data show that the groundwater level of the shaft is at 1 m, and the hydrostatic pressure is 50 KPa, 80 KPa and 150 KPa at different depths, but the void water pressure at the site is much higher than the hydrostatic pressure, which indicates that there is groundwater seepage. For the treatment of groundwater seepage field, “water-soil calculation” or “water-soil combination” method should be selected based on the engineering geological conditions. For the water-saturated sand and pebble layer, water-soil calculation is usually adopted, but the group believes that groundwater seepage should be taken into account for the calculation. According to Figure 8, during the construction of the shaft, the seepage field changes in small amplitude, the first decline and then rise, the void water pressure with the depth change is a “hyperbolic” trend, the entire construction process did not appear in the pit gushing water. This shows that when the measures to prevent pit water influx are realized during the construction process, the change of seepage field around the shaft is limited by the excavation and lining of the shaft.

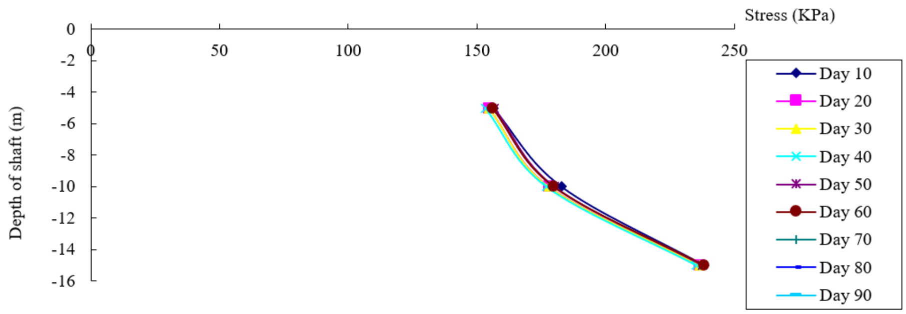


Figure 8. Relation curve of pore water pressure along depth at 6 m-16 m depth.

### 4.5 Analysis of construction monitoring data for soil pressure changes behind the wall

According to Figure 9, the earth pressure is the largest at the depth of about 4 m, and changes significantly with the excavation of the soil body in the shaft, up to 420 KPa, far more than the active and static earth pressure of Rankine's theory. The earth pressure below 5 m is smaller and does not change much, mostly between the active and static earth pressure, and the relationship of the change of the depth is not obvious, which is inconsistent with the traditional theory. However, considering the principle of earth pressure generation, the soil displacement after the wall is small, forming a fixed displacement boundary, resulting in an insignificant relationship between earth pressure and soil self-weight. And the ground pile load has a large impact on the upper earth pressure, which affects the depth of about 4.5 m, so the impact of ground pile load should be emphasized during the construction of diaphragm wall.

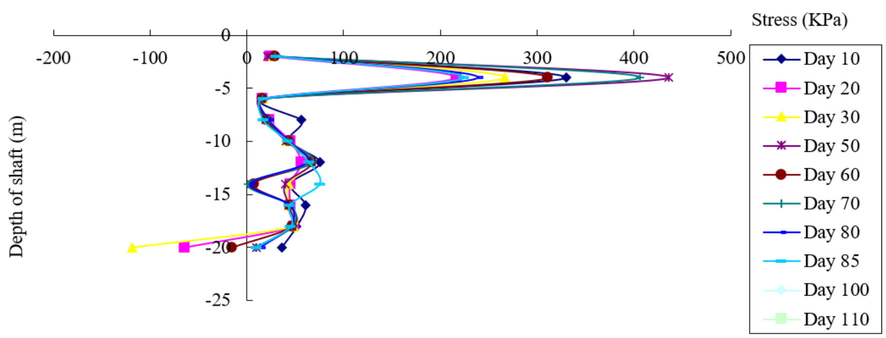


Figure 9. Pressure-depth relationship curve of soil outside the wall at depths of 2 m-18 m.

### 4.6 Analysis of construction monitoring data for horizontal displacement of soil behind walls

The analysis of the monitoring data shows that the horizontal displacement of the soil body behind the wall is within 2 mm according to Figure 10, which is almost negligible, and there is no significant change in the horizontal displacement along the depth of the shaft, which, from one side, reflects the influence of the self-stabilizing effect of the circular shaft on the soil pressure and strain of the soil body behind the wall. The soil pressure on the soil body behind the wall did not reach the active state or even the static soil pressure state.

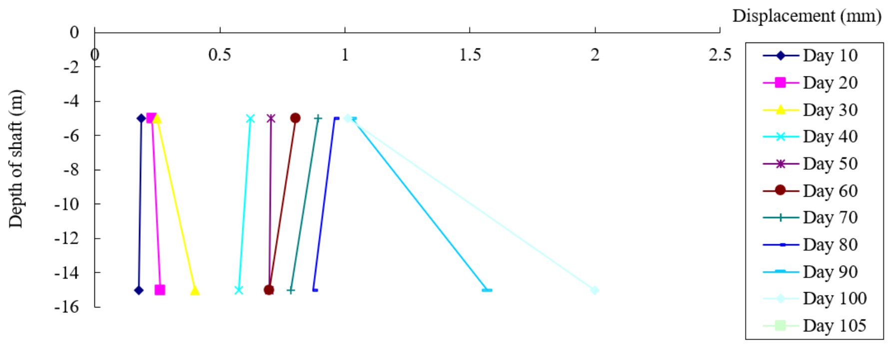


Figure 10. Relation curve of soil displacement change along depth outside the wall from 5 m to 15 m depth.

## 5. CONCLUSION

This paper relies on the construction monitoring project of the circular shaft diaphragm wall of the Nantanhai shield, and carries out an in-depth study on the construction monitoring of the circular shaft diaphragm wall. The following conclusions were drawn from analyzing the monitoring data:

First of all, circular diaphragm walls cannot be calculated simply as foundation beams, but should be regarded as axisymmetric structures, taking into account the soil pressure as a function of shaft size. The force arch effect can be quantitatively expressed by shaft diameter, thickness or ratio, which is closer to the actual loading situation. Secondly, the pore water pressure is higher than the hydrostatic pressure, indicating the existence of groundwater seepage. The seepage field should be treated by soil-water fractionation methods to guide waterproofing and drainage measures. In addition, the earth pressure monitoring showed that the depth of ground pile load influence was about 5 m, and the earth pressure decreased after the circular wall was stabilized. The special force characteristics of circular shaft diaphragm walls need to be considered to avoid structural safety problems. Finally, the wall strain and soil displacement data behind the wall reflect the mechanical behavior of the circular shaft diaphragm wall. The self-stabilizing effect of the soil body of small and medium-sized circular retaining walls is obvious, which helps to reduce the lateral earth pressure.

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