Reliability Analysis of Bearing Capacity of Pile Foundation of Continuous Rigid Frame Bridge During Construction

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Abstract: As the basis of the entire bridge project, bridge pile foundation is highly related to the safety and durability of the bridge especially in construction quality. In this thesis, the reliability of pile foundation bearing capacity of a super-large bridge under construction was analyzed. Besides the reliability index was calculated. The key factors controlling the construction quality of pile foundation were found to guide the actual project construction.

1. Introduction
In recent years, the improvement of basic transportation has been a hotspot in China. It is predictable that the main goal of China's transportation construction industry is to focus on and intensify the development of basic transportation construction. Bridge project is one of the main parts of the basic traffic. With the rapid constructive development of traffic infrastructure in China, the total mileage of bridge project shows an increasing trend. According to the statistics of the ministry of transport, by 2018 the number of bridges in service in China has exceeded 800,000. Obviously bridges in the construction of transportation infrastructure has become more and more significant, which has gradually become the hot topic in the industry. Looking down the road network from above, the beautiful human rainbow connect the sides of the Taiwan straits, the Yangtze river Yellow River, the poverty alleviation of northwest impoverished mountainous area road, connecting the spread Chinese culture in the road. All the construction of a bridge on the politics, economy and culture cannot be ignored.

The Yangsigang Yangtze bridge, as the 10th Yangtze bridge, which has come into service in Wuhan (with a span of 1700 meters, it has be used in September in 2009). This bridge crosses the Yangtze and has been the longest suspension bridge in China, ranking the second in the world. In addition it is the largest double-desk suspension bridge in the world. The Shanghai-Nantong Yangtze bridge, with a span of 1092 meters, is the largest cross-rail cable-stayed bridge in the world. It is also the first cross-rail cable-stayed bridge with a span of more than kilometers. The section from Danyang to Kunshan of the Beijin-shanghai expressway is the largest bridge in the world, with a total length of 164.851 kilometers. The Hong Kong-Zhuhai-Macao Bridge was officially put into use on October 24, 2018, with a total length of 55 kilometers, becoming the longest sea-crossing bridge in the world. With a total length of 16.34 kilometers, Pingtan strait cross-sea bridge is the world's first real cross-sea bridge. Lijiang Jinsha River Bridge is the world's largest span suspension bridge. China's bridge building technology continues to mature in the terms like "The first seat", "The first highest" and "The first long". However, along with the fast development, the focus and emphasis on the bridge quality and safety are not enough.
What’s more, most of the bridges constructed in the early stage of basic traffic development have stepped into aging period. Bridge accidents is increasing which not only has caused the huge economic loss, but also produced the unexpected and negative social effect.

In 2017, the Longtan Bridge collapsed during the cantilever construction phase; In 2016, a continuous beam bridge on the passenger dedicated line of Shenyang Junction undergoes vertical overturn during cantilever construction; Due to improper construction, the Xiaijianshan bridge collapsed during construction causing 8 deaths and 12 injuries; In 2007, because of the irregular design of the Fenghuangdixi Minjiang Bridge in Hunan, a particularly serious collapse accident occurred during the construction period, causing 64 deaths and direct economic loss of 39.747 million. By analyzing these bridge accidents, most of the reasons are unreasonable design before construction, irregular operation during construction, and inadequate management. The construction of bridge engineering is often in a complex social and natural environment, which is characterized by long period, large amount of engineering, many difficulties in construction, complex internal structure and extensive external connections. These characteristics determine that there must be a large number of uncertain factors affecting the safety, applicability and reliability of the bridge during the construction of the bridge. Firstly, the paper will study the uncertain factors affecting the reliability of the bridge structure during construction, and then strictly control the factors that have a greater influence which can effectively avoid some safety and quality accidents and improve the reliability of the bridge.

This research objective is to study the construction of the HongNong Special Bridge in the south of the section from Luo Sanjie to Henan-Shaanxi border of 310 National Highway. Another objective is to study reliability of bearing capacity of pile foundation during construction. Based on the analysis of the current research status at home and abroad, combined with the methods and process characteristics of large-scale bridge construction in China, the basic theory of reliability analysis and evaluation of bored cast-in-situ piles during construction is established.

2. The research status
The evolution of methods to study the quality, safety and reliability of construction can be divided into three stages: The first stage is for the builder to judge whether the structure will collapse, damage. The accuracy of this method mainly depends on whether the judger has rich experience and lacks theoretical basis. In the second stage, people judge the reliability of the structure according to the safety factor theory. First, the parameters such as allowable stress, safety factor, and ultimate strength of the structure are calculated, and then these parameters are analyzed and compared. This method only considers that the structure is safe when the resistance is greater than the load, and considers the safety coefficient of the whole structure as the same value. But the method did not consider the time-variability of the structure and the characteristics of each component, so the definition of engineering safety is too general, and the research results are too conservative and lack of scientific nature. In the third stage, reliability is used to represent the probability of achieving the desired goal. By calculating the reliability during the construction of the structure, the safety, quality and reliability of the structure are detected and optimized. Based on probability theory and mathematical statistics, the uncertainty of all important parameters of the structure during the design and construction process is fully and scientifically considered.

As the first bearing part of the overall bridge structure, pile foundation must be reliable to meet the design requirements in order to ensure its stability in the whole life cycle of the bridge. Due to the complexity and concealment of geotechnical properties, the reliability of foundation engineering is less studied than that of structural engineering. Zhang Xuefeng [1] studied the effects of soil cohesion $c$, the stiffness of the pile side and the soil at the end of the pile, the length of the pile, the diameter of the pile and other parameters on the bearing capacity through several sets of comparative tests changing the single variable in the test. Zhou hongbo [2] studied the influence of pile side mud and pile bottom sediment formed by the construction technology of bored pile on the bearing capacity of pile foundation. Singh G[3], Huh J[4]. conducted reliability analysis on the bearing capacity of structural pile foundation based on reliability theory, which provided enlightenment for the reliability analysis of bridge pile
foundation. Zhou Jianfang [5], Zheng Junjie [6], Wang Feng [7] introduced the calculation method of the reliability index of the bearing capacity of bridge pile foundation under different failure criteria. Miao Linchang [8] compared the advantages and disadvantages of the pile foundation bearing capacity measurement methods specified in different national codes. Weng Guangyuan [9] analyzed the factors that affect the vertical bearing capacity of bored cast-in-situ piles and the commonly used methods to predict the bearing capacity of the pile, and proposed the application of neural network method to predict the bearing capacity of the pile. Ma Ye [10] gave the calculation formula of pile lateral friction and the calculation formula of reliability, and obtained the probability distribution type and statistical parameters of pile lateral friction based on the data analysis of 105 test piles, which can be used for the calculation of the same type.

3. Analysis of influencing factors on bearing capacity of pile foundation during construction period

In bridge engineering, as a part of the substructure, pile foundation plays a role in transferring load, reducing the overall settlement and improving the bearing capacity of the foundation. The calculation formula for the axial compressive bearing capacity of a single bored pile is shown as follows:

$$R = R_{\text{pile end}} + R_{\text{pile side}} = \frac{1}{2} \pi d \sum_{i=1}^{n} q_l l_i + A_p q_r$$  \hfill (1)

Analysis of the calculation formula (1) for the axial compression bearing capacity of a single pile can be seen: The pile foundation bearing capacity is composed of the pile side friction resistance and the pile end bearing capacity; The factors that affect pile lateral friction include pile diameter, pile length and the friction between soil layer and pile side. Combined with the construction technology of bored pile, the factors influencing the bearing capacity of pile foundation are divided into three parts: pile geometry, soil characteristics and pile forming technology.

3.1. Pile geometry

References [1, 11, 12] studied the effects of pile length and diameter of bored cast-in-situ piles on bearing capacity and settlement of pile foundations. The method of controlling variables was used to control the vertical load Change, change the pile length, observe the changes in the settlement and bearing capacity of the pile foundation, the results showed: When the pile length changes between 20 and 40 meters, the settlement of the pile foundation changes significantly, but the bearing capacity does not change much. When the variation range of the pile length is 40 ~ 60 meters, the settlement of the pile foundation is not obvious. When the variation range is 60 to 80 meters, the settlement is basically unchanged, but when the pile length is greater than 40 meters, the bearing capacity of the pile foundation will increase significantly with the increase of the pile length. This is because when the bored cast-in-place pile length exceeds 40 after the meter, the proportion of the frictional force of the pile side to the total bearing capacity of the pile foundation increases, and the characteristics of the friction pile become more obvious. Different pile body lengths have different types and properties of the soil at the end of the pile, so the length of the pile also has a certain effect on the bearing capacity of the pile end. Control the pile length and other soil parameters unchanged, change the pile diameter, and the bearing capacity of the pile foundation also increases with the increase of the pile diameter. Therefore, for general pile foundations, changes in pile length and diameter have a significant effect on the bearing capacity of the pile foundation. Moreover, due to the uncertainty of construction technology type, construction management level and human factors, the randomness of pile geometry parameters should not be ignored in the study of pile bearing capacity reliability.

Literature [14] points out that the construction of bridges at the present stage generally adopts the infrastructure supervision system. According to investigations, the actual over-under-irrigation length of bored cast-in-place piles generally does not exceed 10 cm. For super-long piles with a pile length exceeding 80m, the over-underfill length is negligible. The literature also made a statistical analysis on the test ratio of a total of 335 pile foundation hole diameters in 8 Bridges, the research results show that
the ratio of hole formation test of pile foundation obeys the maximum value type I distribution, the maximum value is 1.130, the coefficient of variation is 0.110, and the minimum value of 95% hole formation is 0.995. So, in the high-level construction management process, the deviation of the hole diameter is small and can be ignored.

3.2. Soil properties
It can be known from Formula 1 that the bearing capacity of the pile-end soil and the frictional resistance of each soil layer within the drilling depth are important uncertain parameters for calculating the bearing capacity of the pile-end. Zhang Xuefeng [1] chose to control the geometry of the pile body, and changed the cohesion of the soil at the end of the pile and the side of the pile in turn. The results show that the increase of soil cohesion has little effect on the bearing capacity of pile foundation; if the shear modulus of the soil on the pile side is less than 10 Mpa, the bearing capacity and settlement of the pile foundation will change significantly with the shear modulus. When the shear modulus is greater than 10 Mpa, it should be taken into the calculation as a fixed value. Ma Ye [97] collected the geometric dimensions and test values of lateral friction resistance of 105 test piles passing through a single kind of soil layer, calculate the frictional resistance per unit area of various types of soil through Equation 2 and calculate the corresponding statistical parameters.

\[ R_{\text{pile side}} = U \sum_{i=1}^{n} q_i \]  

(2)

3.3. The process of pile
In the process of drilling cast-in-situ piles, drilling mud of suitable consistency needs to be prepared in advance, the mud forms a layer of mud on the wall of the hole, which can effectively block the seepage inside and outside the hole and prevent the hole from collapsing. However, since the bearing capacity of super-long piles mainly comes from the frictional force on the side of the pile, if the thickness or strength of the mud skin formed on the hole wall is not suitable, it will greatly affect the quality of the pile. Zhou Hongbo [2] studied the influence of mud skin strength and mud skin height on lateral friction of pile, the research results show that the increase of the strength of the mud skin reduces the frictional loss of the pile foundation; the longer the length of the pile body, the greater the influence of the mud skin height on the bearing capacity of the pile foundation.

Part of the drilling slag generated in the drilling process is carried out of the hole by mud, and the rest is removed by cleaning hole after drilling. Even so, there will still be a small amount of sediment at the bottom of the pile after drilling. On the one hand, the existence of dregs at the bottom of the pile changes the properties of the soil at the pile end, making the mechanical properties of the soil at the pile end worse, on the other hand, reducing the effective pile length of the pile body. When the sediment reaches a certain thickness, the bearing capacity of the pile end is only related to the properties of the sediment and has nothing to do with the soil at the pile end [13]. Literature [2] and Wong studied and analyzed the influence of sediment on the bearing capacity of pile foundation by changing a single variable. The research results show that the bottom sediment has a significant effect on the bearing capacity of the pile, it decreases with the increase of sediment thickness.

4. Reliability of axial bearing capacity of bored pile during construction period.
As the foundation of the whole project, the reliability of the bridge pile foundation is related to the quality and safety of the subsequent construction of the whole project. When studying the reliability of the axial bearing capacity of single pile during the construction period, we take the most unfavorable condition during the construction of bored pile——Cast - in - place pile is finished

4.1. The Function
The influencing factors of bearing capacity reliability during construction can be divided into resistance effect and load effect. When variable loads such as live load during construction and impact load during concreting are taken into account, the limit state function of axial bearing capacity of single pile during
construction of bored pile of continuous rigid frame bridge is shown in formula (3):

\[ Z = R - S_G - S_Q \]  \hspace{1cm} (3)

4.2. Bearing capacity probability model and statistical parameters

We define structural resistance as the ability of the structure to resist the load applied to it, denoted by the letter R. From the above analysis, most of the factors that affect structural resistance are random, we treat the construction resistance as a function of multiple random variables \( R = f(X_1, X_2, \ldots, X_n) \) (\( X_i \) represents the main random variable that affects structural resistance). From the perspective of probability statistics, to study the probability distribution model and statistical parameters of structural component resistance, a large number of resistance data samples from the same component actually measured under the same conditions are required, which cannot be achieved in actual engineering. In order to expand the sample size, a dimensionless random variable \( \lambda_R \) is introduced to normalize the obtained data for statistical calculation.

\[ \lambda_R = \frac{\text{Measured value of axial ultimate bearing capacity}}{\text{Formula calculated value}} = \frac{R}{R_k} \]  \hspace{1cm} (4)

Zhang Shuting [14] collected 44 complete test pile data from different bridge projects; Reference [14] carried out a statistical analysis of the ratio of 335 pile foundation hole diameters of 8 bridges; Ma ye [10] collected the geometric dimensions and test values of lateral friction resistance of 105 test piles passing through a single kind of soil layer; Many scholars at home and abroad have come to the same conclusion through analysis of different test pile samples: the axial bearing capacity of bored pile of bridge is subject to both normal distribution and lognormal distribution, but lognormal distribution is more appropriate.

4.3. An engineering example

A large bridge has 374 pile foundations and 288 main pile foundations. The designed pile diameters are 1.6m and 1.8m, and the pile lengths range from 42m to 93m, which are friction piles, the pile foundation passes through various layers such as loess silt layer, pebble layer, fine sand layer, clay layer, etc. In order to expand the sample size, dimensionless random variables \( \lambda_R \) were introduced. Correspondingly, the dimensionless trial ratio expression of permanent load \( S_G \) and variable load \( S_Q \) is as follows:

\[ \lambda_G = \frac{\text{Actual constant load value}}{\text{Constant load effect standard value}} = \frac{G}{G_k} \]

\[ \lambda_Q = \frac{\text{Actual live load value}}{\text{Live load effect standard value}} = \frac{Q}{Q_k} \]  \hspace{1cm} (5)

The corresponding limit state equation of pile foundation bearing capacity is:

\[ \lambda_p - \frac{\lambda_{ci}}{K(1+\rho)} - \frac{\lambda_Q \cdot \rho}{K(1+\rho)} = 0 \]  \hspace{1cm} (6)

Due to the lack of data on the bearing capacity of the Hongnongtuo Bridge, comprehensive and reliable statistical results cannot be obtained. Taking literature [14, 15, 16], American AASHTO code, building structure load code, etc., we take \( K = 2.0, \rho = 1.0, 2.0, 2.5, 3.0, 3.5, 4.0 \), The necessary statistical parameters are shown in Table 1.
Table 1. Statistical parameters of $\lambda_p, \lambda_G, \lambda_Q$

| Random Variables | $\mu$   | $\sigma$  | $\delta$  | Distribution type          |
|------------------|---------|-----------|-----------|-----------------------------|
| $\lambda_p$      | 1.077   | 0.183     | 0.169     | Lognormal distribution      |
| $\lambda_G$      | 1.015   | 0.042     | 0.043     | Normal distribution         |
| $\lambda_Q$      | 1.152   | 0.157     | 0.181     | Normal distribution         |

The calculation results of the reliability index of the axial bearing capacity of a single pile are shown in Table 2 and Figure 1.

Table 2. Calculation results

| Number of iterations | $\rho=1.0$ | $\rho=2.0$ | $\rho=2.5$ | $\rho=3.0$ | $\rho=3.5$ | $\rho=4.0$ |
|----------------------|------------|------------|------------|------------|------------|------------|
| 1                    | 2.8076     | 3.2114     | 2.6695     | 2.6450     | 2.6258     | 2.6102     |
| 2                    | 3.6828     | 3.2762     | 3.3468     | 3.2918     | 3.2495     | 3.2159     |
| 3                    | 3.6915     | 3.4330     | 3.3606     | 3.3062     | 3.2643     | 3.2309     |
| 4                    | 3.6915     | 3.4339     | 3.3607     | 3.3064     | 3.2644     | 3.2311     |

Figure 1. Reliable index of axial bearing capacity of single pile with different load ratios

4.4. Parameter sensitivity analysis

In order to find out the important factors influencing the reliable index, we used the control variable method to study the sensitivity of the parameters of the function. In order to facilitate our calculation, we take $K = 2.0, \rho = 1.0$, keep other parameters unchanged, change the parameter mean one by one. Observe the changes of reliable index, the calculation results are shown in Table 3. Figure 2 shows the change trend of the reliable index of each variable under different coefficients of variation.

Table 3. Reliable index of bored piles under different coefficients of variation

| average value | $0.8\mu$ | $0.9\mu$ | $1.0\mu$ | $1.1\mu$ | $1.2\mu$ |
|---------------|----------|----------|----------|----------|----------|
| $\beta/\lambda_p$ | 2.4616   | 3.1101   | 3.6915   | 4.2184   | 4.7002   |
| $\beta/\lambda_G$  | 4.1741   | 3.9293   | 3.6915   | 3.4605   | 3.2360   |
| $\beta/\lambda_Q$  | 4.2415   | 3.9619   | 3.6915   | 3.4298   | 3.1765   |
The sensitivity of the research parameters is generally set to a range of -10% ~ 10%. In order to highlight the sensitivity of the reliable index of the bearing capacity of the bored piles during construction, the average value of the parameters is calculated to change between -20% ~ 20%. It can be clearly observed from Figure 5.2 that the change in the resistance index of the bearing capacity of the bored pile during construction is the most sensitive. With the increase of the average value of the axial bearing capacity of a single pile, the reliability index shows a linear growth trend, and the average value increases by 10%, which is reliable. The maximum increase of the index is 17.57%; The sensitivity of the reliable index to the variable load and the permanent load is not much different, but the impact of the change of the load on the reliable index is not obvious, but it cannot be ignored; the bearing capacity of the bored pile during construction The reliability index decreases linearly with the increase of the load average. For every 10% increase in the permanent load average, the reliability index decreases by 6.44%; for every 10% increase in the variable load average, the reliability index decreases by 7.58%. In addition, we can see from Figure 1 that the value of different load ratios has little effect on the reliability of the bearing capacity of the pile foundation during construction.

5. The quality control
From the results of parameter sensitivity analysis, it can be known that increasing the bearing capacity of the pile foundation is the most effective way to improve the reliability of the axial bearing capacity of a single pile during construction. In the second section of the article, a comprehensive study has been made on the composition and influencing factors of the resistance of bored piles. The geometry of the pile body, the thickness and strength of the mud and sediment are related to the actual construction process of the pile foundation, and the nature of the soil. It depends on the geological environment of the project area. Therefore, whether the level of the construction personnel meets the requirements, the construction technology adopted is advanced, and the site construction management is strict are the factors that should be considered first when the reliability index is low. In addition, controlling the load effect of the pile foundation during the construction process is also an important way to improve the reliability of the bearing capacity of the pile foundation during construction. The Hongnongjian Bridge is one of the most difficult and difficult projects for the southward movement of National Highway 310. The 374 pile foundation is also one of the hardships of Hongnongjian Special Bridge. The engineering characteristics of the project are as follows:
(1) The geological conditions and geographical environment of the test pile site should be the same as or similar to the project site. The selection of the drilling rig is determined by the test pile. The construction process is adjusted according to the geological conditions. Whether the equipment and material configuration are reasonable. Optimize the pile length, diameter, and number of piles to achieve the goals of economy, safety, and use.

(2) Do a good job of geological exploration before construction, find out the composition of groundwater and underground soil layer to avoid the occurrence of unknown formations or groundwater surges, adjust the mud index in time according to the geological situation, control the drilling speed, and ensure that the mud wall is good.

(3) To ensure the quality of clearing holes, stop the clearing of the holes after the mud index and sediment at the bottom of the holes reach the allowable range.

(4) During hole formation inspection, strictly check the verticality of the pile body and the size of the pile body.

(5) The pouring of the pile foundation concrete is carried out in strict accordance with the construction specifications and design requirements.

(6) Both the construction stage and the maintenance stage should control the load on the pile foundation, and the loads that should not occur should be removed in time. It is best to apply the load in the form of a uniform distribution on the range of the pile foundation to avoid significant bias and damage to the pile foundation. Force performance, affecting the overall bearing capacity.

6. Summary
In recent years, bridge construction has gradually increased the bearing capacity of engineering foundations, facilitating super-long large-diameter piles to be used in large numbers. The pile foundation is the foundation of the entire bridge project. The reliability of the bearing capacity of the pile foundation is related to the quality of the entire bridge and it is safe, and the pile foundation is an underground concealed project. All the defects and instabilities existing in the pile foundation cannot be completely detected by means of acoustic detection. Therefore, analysis and calculation of the reliability of the bearing capacity of the bridge pile foundation during construction is an important way to ensure the quality of the bridge construction. In this paper we calculated the axial bearing capacity reliability and parameter sensitivity analysis of the Hongnongjian Bridge pile foundation during construction. It is found that the axial bearing capacity of a single pile is an important factor affecting the reliability index. ?Diameter, improve the strength of the mud, and reduce sediment at the bottom of the pile.

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