The Safety Automatic Monitoring System of Ancient Seawall Based on Vibration Control

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Abstract: With the development of Chinese economy and society, infrastructure and engineering construction projects continue to increase. There are often construction projects such as wharfs, bridges and houses in the areas near the ancient seawall, which will affect the ancient seawall to a certain extent. Using IoT automated monitoring methods to realize the remote real-time monitoring and early warning of the ancient seawall of Qiantang River, and analyze the impact of vibration caused by the construction on the ancient seawall. In the meantime, safety automatic monitoring system of the ancient seawall based on vibration control was developed. The paper through the application of three experiment cases, analyze the impact of construction near the seawall, which has certain application value for the protection of the ancient seawall, daily operation management, and construction guidance of projects near seawalls.

1. Introduction
The ancient seawall of the Qiantang River has a long history and has played an important role in preventing floods and tides for hundreds of years. It is an significant barrier for flood control in the Qiantang River estuary area. Since its operation, the ancient seawall has some problems such as part of the pond roof subsides too large, weathering of the wave wall, partial cracks in the fish scale stone pond, weak erosion resistance of the pond protection structure, insufficient flood defense capability, and serious erosion damage at the bottom of the embankment [1~2]. In order to eliminate the hidden safety hazards caused by these problems, the ancient seawall has been reinforced one after another. At the same time, with the continuous increase of infrastructure and engineering construction projects, there are often construction projects such as wharfs, bridges and houses in the areas near the ancient seawall, which will affect the ancient seawall to a certain extent. Such as the pile sinking construction in seawall reinforcement.

The main impact of piling construction on the ancient seawall is resonance when the vibration frequency of piling is close to that of the ancient seawall itself. It will cause serious damage to the seawall structure, and the groundwater level in coastal areas become generally higher. For saturated loose fine sand, silt sand or clay with shallow distribution depth, when it is subjected to vibration, it is very easy to liquefy the foundation soil, which affects the stability and structural safety of the ancient seawall. Regarding the impact of pile driving vibration on surrounding buildings, many scholars have carried out relevant research, and the methods used are mainly on-site testing, numerical analysis or a combination of the two. Daoping Yao[3] and others used the actual measurement method to comprehensively evaluate the impact of pile driving vibration. Bibing Xu[4] established a pile force
model and studied the attenuation law of pile driving vibration. Henke S[5] used finite element method to study the main control factors that affect the adjacent structure during the piling process. Regarding the impact of vibration on ancient buildings, there are more researches on the impact of rail transit vibration, tunnel blasting vibration, etc. on ancient buildings currently[6~7]. "Technical specifications for protection of historic buildings against man-made vibration"[8] stipulates corresponding allowable vibration standards for ancient buildings of different structures according to their protection levels. And take the horizontal vibration speed of ancient buildings as the evaluation quantity, including many structure types of ancient buildings such as palaces, halls, pavilions, towers, and grottoes. However, this type of ancient seawall is not involved. As a barrier against floods and tides and historical and cultural heritage, the protection of the ancient seawall has more pertinence and higher requirements.

At present, the monitoring of the ancient seawall is mainly based on manual monitoring, including conventional monitoring of settlement and displacement, without considering the impact of vibration on the ancient seawall during the construction process. The study bases on the protection of cultural relics and guarantees safety, and comprehensively considers the impact of vibration caused by the construction near the ancient seawall. Then an automatic safety monitoring system for the ancient seawall based on vibration control has been established to conduct real-time safety monitoring and early warning of the ancient seawall’s vibration, understand the impact of the construction process on the ancient seawall, and take timely measures to reduce the hazards and ensure the safety of the ancient seawall.

2. Project overview
This paper selected three ancient sea ponds in Haining Yulinshitang during the Ming and Qing Dynasties, Haiyan second-line Yulinshitang, and Haiyan Linjiang Yulinshitang, and established an automatic safety monitoring system for the ancient seawall based on vibration control. Carry out the ancient seawall safety automatic monitoring experiment (hereinafter referred to as experiment one, experiment two, experiment three), to study the impact of construction near the seawall.

The study area of experiment one is Yulinshitang during the Ming and Qing Dynasties. The flow of the river is complex, and some beaches have changed greatly. It still relies on the existing 4m wooden piles to act as the anti-scouring capacity of the seawall at the strong tidal wave section of the Qiantang River estuary. The safety guarantee is insufficient, and there have been problems such as part of the pond roof subsides too large, weathering cracks in the wave wall, and cracks in the local fish-scale stone ponds. The construction scene of the project is to carry out the erosion prevention and reinforcement experiment at the bottom of the embankment section, and the construction content is the construction of C60 prestressed reinforced concrete sheet piles with a length of 10m on the outside of the second tank. There are three types of construction piles: H-type piles, U-type piles and centrifugal sheet piles. 600 excavators with vibrating chuck are used for construction, and the construction machinery is located on the road behind the pond top. The experiment one is to monitor the inclination and vibration of the seawall during the construction period of the reinforce the sinking pile. The experiment period is 5 days in total.

The study area of experiment two is Haiyan second-line Yulinshitang. There is a commercial complex project under construction outside the second-line seawall, and the underground wall of the commercial complex is about 15m away from the second-line seawall. The gentle slope of the seawall block stone foundation extends to the project basement, and the elevation of the seawall foundation bottom and basement cap bottom are basically the same. The construction scene of the project is the pile sinking construction of a commercial complex construction project. The construction sequence is to carry out partial pile sinking far away from the second-line seawall first, and then the piles close to the second-line seawall. The construction pile type is a PHC prestressed pipe pile with a pile diameter of 500 mm, which is driven by a hammer-driving pile machine. The experiment two is to monitor the vibration of the seawall during the pile sinking construction period of the commercial complex construction project. The experiment period is 63 days in total.

The study area of experiment three is Haiyan Linjiang Yulinshitang, and there is a wharf
reconstruction and expansion project near the pond. The construction scene is the pile sinking construction of the reconstruction and expansion project of the wharf. The pile type is PHC1000B pipe pile, which is implemented by water hammer piling ship, and the hammer type uses D100 diesel hammer. The experiment three is to monitor the vibration of the seawall during the pile sinking construction period of the reconstruction and expansion project of the wharf. The experiment period is 42 days in total.

3. Vibration monitoring
Three experiments combined the geological conditions of the ancient seawall, project overview, construction plan and automatic monitoring requirements, etc., and used automatic monitoring equipment to monitor the vibration of the ancient seawall. Vibration will occur during the construction of piles, which may cause the seawall structure to loosen, reduce the safety factor of the embankment body, and affect the stability of the seawall. The vibration degree of the seawall is judged by monitoring the seawall vibration, and help to further judge the impact of construction on the seawall.

There are 4 automatic monitoring equipments for experiment one, three for experiment two, and three for experiment three. In the first experiment, the experiment points are arranged in a longitudinal section. In the second experiment, the experiment points are arranged in a transverse section. And the experiment three is the same as the first experiment.

4. Safety automatic monitoring system of the ancient seawall
The security automatic monitoring system of the ancient seawall adopts a service-oriented architecture design. With the help of IoT sensing technology, the system focuses on the safety of the ancient seawall to form a data chain from safety monitoring, data analysis to prediction and early warning. The system realizes information collection automation, intelligent monitoring and early warning, and business and office integration. Finally, a visualized safety monitoring and management system for the ancient seawall has been formed to improve the informatization and intelligence level of monitoring and early warning work.

4.1. System framework
The security automatic monitoring system of the ancient seawall adopts the B/S structure mode and is deployed in the cloud mode. It consists of a data collection layer, a network layer, a data management layer, a data analysis layer, and an application layer. The data collection layer includes vibration data collection, tilt data collection, crack data collection, manual monitoring data filling and reporting, external data import, etc. The network layer includes wired and wireless, wired includes operator private lines and VPNs, and wireless includes 3G/4G/5G networks. The data management layer includes data resources such as basic databases, model libraries, algorithm libraries, automated monitoring databases, and geographic information databases. The data analysis layer is to perform data statistics, cleaning, mining, and visualization of the acquired basic data, monitoring data, etc., and perform threshold analysis, characteristic value analysis, comparative analysis, and structural safety status evaluation. The application layer is to provide an operating platform for the safety monitoring of the ancient seawall, including subsystems such as comprehensive display, monitoring management, statistical analysis, data entry, early warning management, and system management.

4.2. System functions
The safety automatic monitoring system of the ancient seawall mainly has six functional modules. The first is information query and maintenance. The system integrates multi-source data such as project basic information, real-time monitoring data, and entered manual observation and inspection data, and realizes spatial data information query based on GIS maps. The second is real-time collection and transmission. The system establishes an IoT perception network, connects to automatic monitoring and data collection equipment, and conducts real-time and automatic online monitoring and data collection on the inclination, cracks, vibration and other conditions of the seawall and transmits it to the system
server. The third is data statistics and analysis. Total statistics, extreme statistics, mean statistics, time history change analysis, comparative analysis, regression analysis, etc. are performed on real-time monitoring data and entered manual observation data, and monitoring reports are automatically generated according to custom templates. The fourth is intelligent inspection and maintenance. The inspection data, positioning data, status process information, maintenance and maintenance information can be uploaded in real time through the mobile phone to improve the efficiency of inspection work and the level of inspection management. The fifth is early warning and threshold management, the system manages early warning thresholds and real-time and historical early warning conditions. By adding "monitoring category", "monitoring item", and "alarm value", the early warning threshold setting of a certain site, or a certain type, or a single device can be realized. Then the system will carry out hierarchical early warning based on the threshold value exceeding the limit. The early warning methods include linked sound and light alarms, SMS notifications, email notifications, platform pop-up windows, etc. The sixth is background management, through which functions such as user management, authority management, function module management, information security management, measurement point management, equipment management, calculation formula and chart management, and model management can be realized.

4.3. System applications
The system is connected to the data of automatic monitoring equipment deployed on-site in experiment one, Experiment two, and experiment three. The system monitors the vibration conditions of the ancient seawall in the experiment section in real time, and provides windows for displaying, querying and downloading monitoring data. Intuitively display the changes of monitoring data in the form of two-dimensional charts, automatically generate monitoring reports, and have data analysis functions such as online extreme value and average value statistics, time history change analysis, and monitoring item comparison analysis. According to preset thresholds, hierarchical early warning can be realized. The system is divided into a standard version and a large-screen version. The application of the system can timely understand the safety status of the ancient seawall and control risks, which can meet the needs of business work related to the safety management of the ancient seawall and improve the daily safety operation and management level.

5. Monitoring results analysis
During the experiment, experiment one uses the excavator with the vibrating chuck method to carry out the pile sinking construction, and the construction machine is located on the road behind the top of the pond; experiment two uses the hammer method to carry out the pile sinking construction, and the construction machine is located in the foundation pit outside the seawall; experiment three uses the hammer method to carry out the pile sinking construction, and the construction machine is a water hammering pile driver. According to the "Safety regulations for blasting"[9], "Standard for allowable vibration of building engineering"[10] and other standards and regulations, the vibration criterion adopts the peak vibration speed and main vibration frequency of the basic particle where the protection object is located. Vibration monitoring should measure the three vertical components of the particle vibration at the same time, and take the maximum of the three components as the peak vibration velocity of the particle. During the pile-sinking construction in the experiment, the vibration velocity and acceleration response of the measuring points were monitored in real time through the vibration sensor to analyze the impact of vibration on the measuring points during the pile-sinking construction process.

The statistics of peak vibration velocity in each experiment are as follows:

| Experiment name | Peak vibration velocity (cm/s) | Piling method | Piling position | Remark |
|-----------------|-------------------------------|---------------|----------------|--------|
| Experiment one  | 0.9277                        | excavator with vibrating chuck | Bottom of the pond | The construction machinery is located on the top of the pond, and |
Analysis of the vibration monitoring data during the experiment period shown that when the site of pile-sinking construction is closer to the seawall, the monitored vibration velocity is generally large; when the site of pile-sinking construction is far from the seawall, the monitored vibration velocity is generally small, and the attenuation of vibration energy is obvious. The monitoring data is analyzed both in time domain and frequency domain. Kalman filtering method is used to eliminate the influence of environmental noise. Typical monitoring results of velocity response and acceleration response are shown in Fig.1 and Fig.2. Channels 1/2/3/4/5/6 in Fig.1 represent the data in the Y and Z directions of the equipment 01/02/03 in experiment three respectively.

| Experiment   | Hammer Method | Distance from the seawall |
|--------------|---------------|---------------------------|
| two          | 0.5370        | 15m from the seawall      |
| three        | 0.0760        | 170m from the seawall     |

Figure 1. Figure with typical monitoring result of velocity response
Figure 2. Figure with typical monitoring result of acceleration response

It can be seen from Fig.1 and Fig.2 that during the period of pile-sinking construction, the velocity response and acceleration response monitored by the vibration equipment are both small, and the variation trend of three equipments in all directions are relatively consistent.

Fourier transform is used for monitoring velocity response in each construction period. Typical spectrum is shown in Figure 3, which demonstrates the relation between vibration energy and vibration frequency within the frequency range. The vibration datas of each sensor are divided into 5 mins and the results of spectrum analysis are shown in Fig.4. It is clearly that vibration energy of each time period during the monitoring period are in agreement.

Analysis of the vibration monitoring data reveals that the distribution of vibration energy of each equipments in each direction is basically the same, though the hammer-percussive pile driving construction are in different areas. During the monitoring period, the distribution of vibration energy is relatively consistent of each time period. The vibration frequency caused by construction is distributed between 2~14Hz. In the subsequent construction process, the vibration frequency generated by pile driving such as hammer-percussive pile driving construction should avoid the above-mentioned frequency range, in order to suppress resonance, reduce vibration amplitude and protect the ancient seawall.
Figure 3. Figure with Spectra of vibration data

Figure 4. Figure with Spectra of vibration data of each time period

For experiment 1, a total of 17 C60 precast piles with 3 different types (8 H-type piles, 1 U-type pile, and 8 centrifugal piles) were used for the pond foot sheet pile construction. The site conditions and
monitoring data illustrate that: 1) the U-shaped pile has no tip, which makes it impossible to smoothly break the soil without a pilot hole. The monitored vibration velocity is generally large due to the heavy impact of pile hammer; 2) The monitoring vibration velocity during construction of H-type piles is generally lower than the centrifugal piles. Normal distribution fitting is applied for monitoring vibration velocity of H-type piles and centrifugal piles to obtain the probability density function curve and related characteristic values. The typical probability density function curves are shown in Figure 5.

![Fig.5 Typical probability density function curve of peak vibration velocity](image)

**Tab. 2 Eigenvalues of peak vibration velocity**

| Project | pile type     | Equipment 01 | Equipment 02 | Equipment 03 | Equipment 04 |
|---------|---------------|--------------|--------------|--------------|--------------|
| μ       | H-type pile   | 0.17615      | 0.15949      | 0.14137      | 0.16928      |
|         | centrifugal   | 0.18548      | 0.16655      | 0.14395      | 0.17718      |
| σ       | H-type pile   | 0.06008      | 0.06678      | 0.04197      | 0.05085      |
|         | centrifugal   | 0.07461      | 0.06721      | 0.04200      | 0.06946      |

It can be seen from Fig.5 and Tab.2 that the peak vibration velocity of H-type piles and centrifugal piles are concentrated in the range of 0.1 to 0.3 cm/s. The overall mean μ and mean square error σ of peak vibration velocity of H-shaped piles are lower than those of centrifugal piles, indicating that the mean value of peak vibration velocity of centrifugal piles is slightly larger and the dispersion is slightly greater. The probability of peak vibration velocity of centrifugal piles exceeding 0.3cm/s is generally greater than H-shaped pile.

Therefore, when the subsequent pile driving construction is carried out in this area, the appropriate pile type can be selected based on the research and actual conditions.

6. Conclusions

(1) Through three field experiments, using automated monitoring methods of the Internet of Things, the ancient seawall of Qiantang River was monitored in real time. The ancient seawall safety automatic monitoring system is developed, which has the real-time remote safety monitoring function and early warning function, solving the problem of the inability to monitor the safety of the ancient seawall in real time. The system can be used for real-time monitoring, early warning of engineering construction, daily operation and management, to reduce the adverse effects of engineering construction on the ancient seawall, and to provide support for the daily operation and management, which has certain application value.

(2) The monitoring data shows that if the pile driving construction is close to the seawall, the vibration might has a certain impact on the ancient seawall. During construction period, the impact of vibration should be avoided as much as possible. Construction methods with less vibration should be
adopted or protective measures should be taken to avoid the structure of the ancient seawall from being
damaged. The frequency of vibration caused by the pile driving construction should out of the resonance
frequency range so that the vibration amplitude could be effectively reduced, and the safety of the
seawall structure could be sufficiently protected.

(3) By controlling the vibration frequency and vibration velocity, real-time monitoring can be carried
out on the safety of the stone structures such as ancient seawall. Pre-prevention and dynamic control
could eliminate current deficiencies that damages could not be found in time. Due to the limited
conditions, lack of equipments and short monitoring time, the arrangement of equipment and monitoring
methods could be further improved. With the accumulation of monitoring data, more results will be
obtained.

References
[1] Wu Youxia..Research on the Failure Mechanism of Qiantang River Ancient Seawall[D].Zhejiang
University ,2012.
[2] Huang Liming, Wu Linghong, Ma Yongming. Reinforcement technology of old seawall on the north
bank of Qiantang River [J]. Zhejiang Water Conservancy Science and Technology, 2005(03):
66-68+77.
[3] Yao Daoping, Zhang Yifeng, Zhuo Qun etc. Comprehensive evaluation of the impact of piling
vibration on the building by the test method [J]. South China Earthquake, 2008,
28(003):80-88.
[4] Xu Bibing. Research on Ground Vibration Caused by Piling [D]. Wuhan University of
Technology ,2007.
[5] Henke S. Influence of pile installation on adjacent structures[J]. International Journal for Numerical
& Analytical Methods in Geomechanics, 2010, 34(11):1191-1210.
[6] Zhang Yijing, Chen Su, Zhou Junjie, etc. A Summary of the Impact of Urban Rail Transit Vibration
on Ancient Buildings [J]. Journal of East China Jiaotong University, 2015, v.32;
No.146(06):1-7.
[7] Zhu Liming, Wu Zhiqiang, Xing Shiling, etc. Experimental Study on the Influence of Tunnel
Blasting Vibration on Ancient Buildings [J]. Science Technology and Engineering,
2017(30):291-295.
[8] Ministry of Housing and Urban-Rural Development of the People's Republic of China. GB/T
50452-2008.Technical code for anti-industrial vibration of ancient buildings [S]. Beijing:
China Construction Industry Press, 2008.
[9] General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic
of China. GB6722-2014.Blasting safety regulations [S]. Beijing: China Standard Press, 2015.
[10] Ministry of Housing and Urban-Rural Development of the People's Republic of China.
GB50868-2013.Permissible Vibration Standard for Construction Engineering [S]. Beijing:
China Planning Press, 2013.