Smart Structures and Systems, *Vol. 20, No. 2 (2017) 163-173*
DOI: https://doi.org/10.12989/sss.2017.20.2.163

Structural health monitoring of a newly built high-piled wharf in a harbor with fiber Bragg grating sensor technology: design and deployment

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(Received December 19, 2016, Revised March 13, 2017, Accepted March 30, 2017)

Abstract. Structural health monitoring (SHM) of civil infrastructure using fiber Bragg grating sensor networks (FBGSNs) has received significant public attention in recent years. However, there is currently little research on the health-monitoring technology of high-piled wharfs in coastal ports using the fiber Bragg grating (FBG) sensor technique. The benefits of FBG sensors are their small size, light weight, lack of conductivity, resistance corrosion, multiplexing ability and immunity to electromagnetic interference. Based on the properties of high-piled wharfs in coastal ports and servicing seawater environment and the benefits of FBG sensors, the SHM system for a high-piled wharf in the Tianjin Port of China is devised and deployed partly using the FBG sensor technique. In addition, the health-monitoring parameters are proposed. The system can monitor the structural mechanical properties and durability, which provides a state-of-the-art mean to monitor the health conditions of the wharf and display the monitored data with the BIM technique. In total, 289 FBG stain sensors, 87 FBG temperature sensors, 20 FBG obliquity sensors, 16 FBG pressure sensors, 8 FBG acceleration sensors and 4 anode ladders are installed in the components of the back platform and front platform. After the installation of some components in the wharf construction site, the good signal that each sensor measures demonstrates the suitability of the sensor setup methods, and it is proper for the full-scale, continuous, autonomous SHM deployment for the high-piled wharf in the costal port. The South 27# Wharf SHM system constitutes the largest deployment of FBG sensors for wharf structures in costal ports to date. This deployment demonstrates the strong potential of FBGSNs to monitor the health of large-scale coastal wharf structures. This study can provide a reference to the long-term health-monitoring system deployment for high-piled wharf structures in coastal ports.

Keywords: high-piled wharf; structural health monitoring; system design; FBG; durability monitoring

1. Introduction

Large civil infrastructure systems such as costal wharfs, bridges over straits, high-rise buildings, big inch pipelines and offshore structures are valuable national assets that must be maintained to ensure economic prosperity and public safety in their service period. It is significant to keep them safe in the production service period. Thus, the ability to evaluate the structural safety condition has been widely pursued by scholars. Generally, visual inspection with limited tools and non-destructive testing (NDT) methods are used to obtain the structural health status (Chang and Liu 2003). However, to perform a fast inspection is usually challenging, particularly under water. Most infrastructures of the wharf in the harbor are under water. Thus, a simple and practical method is needed to collect structural conditions that can perform automatic acquisition without a person on duty.

Structural health monitoring (SHM) enables the assessment of health conditions of civil infrastructures in service, after which proper countermeasures are used to ensure the safety and continuous operation of the monitored infrastructure (Chang *et al.* 2003, Jiang *et al*. 2008, Huang *et al.* 2016). With the update in sensor technology and signal-processing techniques, particularly the advances in fiber Bragg grating (FBG) sensor technology, the SHM methodology has been rapidly developed (Worden *et al*. 2008, Ni et al. 2010, Ni *et al*. 2012, Yi *et al*. 2013a, Li *et al*. 2014, Huang *et al*. 2016). Until recently, numerous SHM methodologies and systems have been proposed, some of which have been applied in full-scale structures such as the Alamosa Canyon Bridge (Doebling *et al*. 1997), Hakucho Bridge in Japan (Abe *et al*. 2000), Tsing Ma Bridge in Hong Kong (Ko and Ni 2005, Chan *et al*. 2006, Ko *et al*. 2009), Canton Tower (Ni *et al*. 2009, Yi *et al*. 2015), and Shenzhen securities trading center building (Ye *et al*. 2012). However, there are few studies on the SHM system in infrastructure in the harbor, such as wharfs, trestles and breakwaters, and on using the FBG sensor technology to establish a structural health-monitoring system for hydraulic structures in the harbor.

Nevertheless, serving as critical gateways for international trade, seaports are pivotal elements in transportation networks. Any disruption in the activities of port infrastructures may cause significant losses from secondary economic effects. The wharf is one of the most important hydraulic structures in the seaports, which is available for ship berthing as well as loading or unloading cargo and passengers up and down. Because of the

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http://www.techno-press.com/journals/sss&subpage=7 ISSN: 1738-1584 (Print), 1738-1991 (Online)

functions of the wharf, the health conditions of the wharf structure are directly related to the safety of the ship harboring and cargo handling. However, chloride ion erosion causes serious rebar corrosion and concrete crack because coastal wharf structures serve in the harsh marine environment, which makes the structural materials naturally age more easily. In addition, many costal wharfs in modern countries have reached their design life and must be replaced or retrofitted to remain in service. Thus, with man-made and natural disasters acting on the wharf, the safety conditions of wharf structures are in a serious challenge. In addition, the quantity of wharfs in harbors is notably large worldwide. For example, to date, there are 31,259 berths in the ports of China, including over 5889 berths in seaports. Wharfs that can harbor over 300,000 tonnage vessels have been built in Tianjin Port, Dalian Port, Qingdao Port and other major coastal ports. The number and size of wharfs in China have reached the top of the world. Since the wharfs in ports have an important role in the development of regional and global economies, to study the SHM technology for wharfs in harbors is notably significant. Therefore, gaining the health status of the wharf structure in the seaport is the key to maintain the production operation safety on the wharf.

The high-piled wharf structure is one of three types of wharf structures that is widely used in the ports with soft soil foundation. However, because of the large deformation of the soft soil foundation, pile-beam node failure may occur. With the soil creep, the lateral displacement of the wharf further increases under the service loads, which will cause damage in pile-beam nodes and even serious wharf structure overturning. Therefore, the real-time monitoring safety condition of the wharf is essential.

Long-term structural health monitoring has become an important mean to assess the structural safety with the testing technology development. Structural-health-monitoring technologies for infrastructures have been extensively studied to assess the safety and durability of the structures. The health-monitoring system can guarantee structural safety. Therefore, setting a long-term health-monitoring system in the new-built high-piled wharf in the seaport to monitor its working state has an important significance to guarantee the safety of production.

At present, optical fiber sensors are most promising in the SHM sensor network (Müller and Baier 2005, Takeda 2005). In particular, an optical-fiber Bragg grating sensor is used to monitor the structural health of civil infrastructures (Moyo 2005, Chan 2006). Writing Bragg gratings into the core of a fiber with fiber photosensitivity was first demonstrated by Hill *et al* (1978). The fabrication of fiber Bragg gratings in a fiber core through its side was reported in 1989 (Meltz *et al.* 1989), which was a significant milestone for FBG sensors. The working principle of FBG sensors is that a series of parallel gratings is printed into the core of an optical fiber, and a narrow wavelength range of light is reflected from the sensors when a broadband light is illuminated. Because the wavelength at the peak of the reflected signal is proportional to the grating period, the axial strain can be measured through the peak shift and temperature. FBG sensors are immune to electromagnetic noise and radio interference (Takeda 2005). The ability to resist corrosion makes FBG sensors durable. Because of the small light signal attenuation when transmitting signal with the fiber, it is proper to setup the sensors with a long distance among one another, which can allow one to read the measurement data tens of kilometers away from the monitoring site such as a wharf in open sea. The multiplexing capability and wavelength-encoded measure and information are distinct advantages of FBG sensors compared to other types of fiber optic sensors. FBG sensors can be easily multiplexed with a single string of optical fiber, which can accommodate tens of FBG sensors. In particular, FBG sensors are non-conductive and not significantly affected by water, so they are suitable for use in severed infrastructures in the sea, whereas the traditional electrical sensors are difficult to work in the water environment for a long time. In this regard, the application of this new technology will have a significant impact on the health and efficiency of civil infrastructure systems (Bugaud *et al.* 2000). However, the practical applications of this type of sensor to actual civil engineering structures have not been widely adopted, although the progress of fiber optic health monitoring is impressive (Vries *et al.* 1998, Li *et al.* 2004a, Ansari 2007), particularly in the field of port engineering.

The main purpose of this paper is to devise and deploy a long-term health-monitoring system on a new-built high-piled wharf structure located in the Tianjin port of China based on its characteristics and the FBG sensor technique. The wharf, which is named South 27# Wharf, is 390 m long and 75 m wide; it will be used for ore transportation and other bulk cargo shipping. The fiber-laser-based wavelength-division-multiplexed (WDM) FBG sensor interrogation techniques and a broadband light source-based multiplexed FBG sensor interrogation system will be used in the project. The main parts of the SHM system are the FBG sensor network, custom-designed multi-sensor control boards, base stations, and monitoring and analysis software. The indices are the strain of the structural components, environmental temperature, structural vibration, obliquity of the piles, and corrosion potential of the reinforced-concrete components to predicate the residual service life of the structure. The installation and experimental setup of FBG sensor arrays in the high-piled wharf are also described. This study will play an important role in guiding the construction of health-monitoring systems on high-piled wharfs and promoting the development of long-term health-monitoring technology in coastal ports.

2. Wharf description

The South 27# Wharf is a high-piled wharf under construction in the Nanjiang Port of Tianjin Port in China (Fig. 1), which is designed for bulk cargo transportation. The mechanical properties of this wharf structure are designed based on berthing 300,000 DWT bulk carriers.

The south 27# common wharf is 390 m long and 75 m wide; it consists of three continuous parts: a 390-m main wharf platform and two 73.3-m side approach bridges.

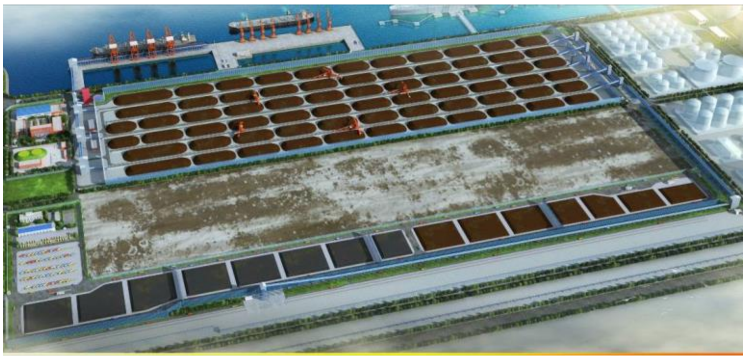
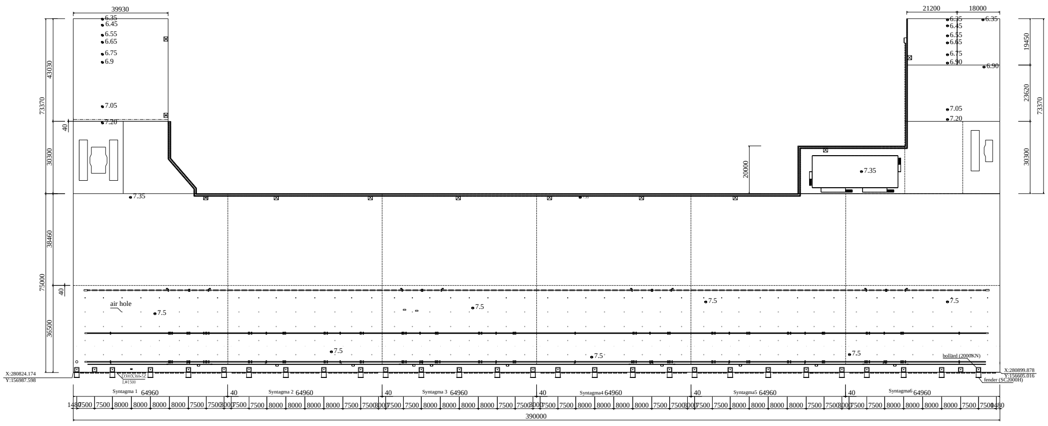
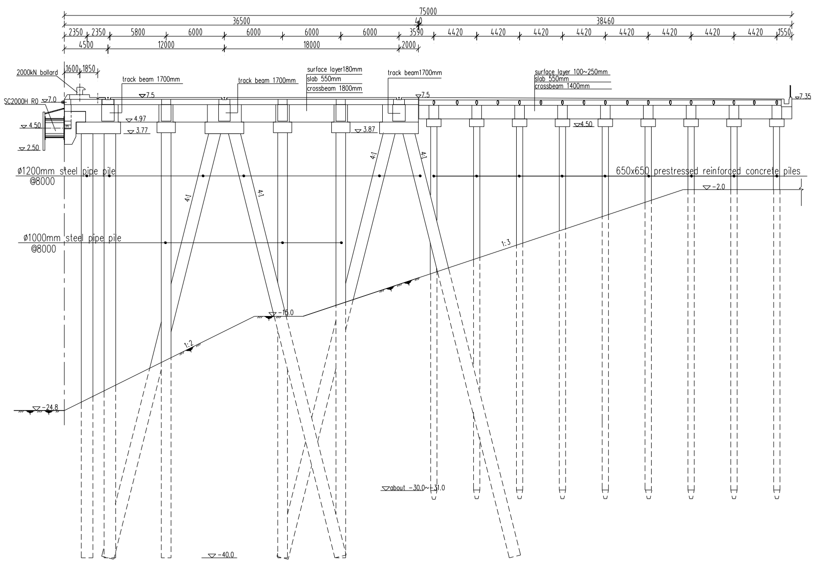


Fig. 1 Perspective of the South 27# Wharf



(a) Elevation



(b) Cross section of the wharf

Fig. 2 Drawings of the South 27# Wharf

The main wharf platform, which consists of nine 65-m syntagmas, is divided into a front platform and a back platform based on the operating requirements. The front platform is 36.5 m wide, and the back platform is 38.5 m wide. Each uniform syntagma of the front and back platforms consists of nine and seventeen bent frames, respectively. The top elevation of the wharf is 7.5 m, and the depth of water at the wharf apron is -24.8 m. Three portal crane tracks are set up on the front platform, and the track beams are supported by steel pipe piles with 1.2-m diameters, whereas steel pipe piles with 1.0-m diameters are used in the remaining locations of the front platform.

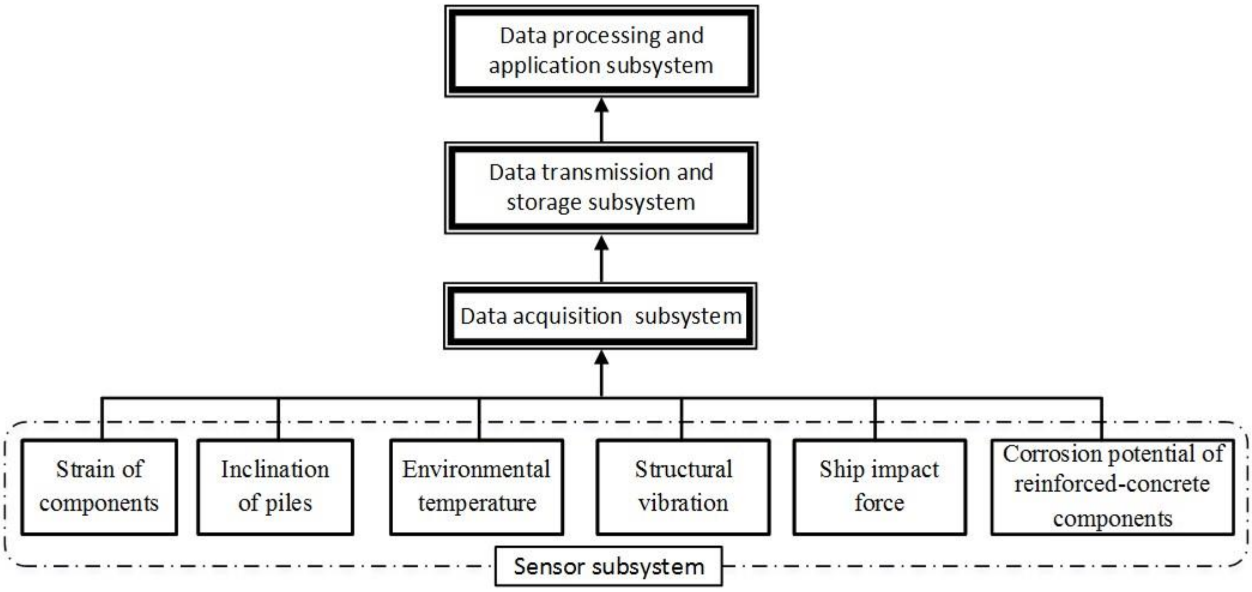


Fig. 3 Structure diagram of the SHM system for a high-piled wharf

The beams in the back platform are supported by 650 mm×650 m prestressed reinforced-concrete square piles. The design uniform loads are 30 kPa from the wharf apron to 18.5 m, 50 kPa from 18.5 m to 36.5 m and 80 kPa from 36.5 m to 75.0 m. The portal cranes, model 40t-45 m, are set up on the front platform. The standard value of the mooring force for a bollard is 1179 kN based on the 200,000 DWT bulk carriers with the 24.4 m/s wind speed and 1379 kN according to 300,000 DWT bulk carriers with identical wind.

Nine steel pipe piles are set in each bent frame of the front platform, including four oblique pile piles and five vertical piles. In each bent frame of the back platform, nine vertical prestressed reinforced-concrete piles are arranged with identical section sizes. The devised SHM system will be set up on the second syntagma of this new-built wharf, and the structural drawing of the wharf is shown in Fig. 2.

The deployed SHM system is mainly devised based on the FBG sensor technique and wireless communication technology. For the SHM system, there are 145 structural comments of the second syntagma of the wharf to arrange sensors, including 289 FBG stain sensors, 87 FBG temperature sensors, 20 FBG obliquity sensors, 16 FBG pressure sensors, 8 FBG acceleration sensors and 4 anode ladders. Based on these sensors, the strain of the components, environmental temperature, obliquity of the piles, vibration of the structure and corrosion potential of the reinforced-concrete components can be monitored in real time. It is significant to obtain the health conditions of the wharf and assess the safety status of the wharf structure.

3. Wharf monitoring system design

Generally, a high-piled wharf mainly consists of a superstructure, a pile and mechanical equipment. Because of the difference in production demand, the wharf is divided into two parts: a front platform and back platform. The front platform is used to load and unload cargo, which is made up of a panel, beam, track beams, pile caps, piles, etc. The force conditions of the front platform are complex because it bears moving mechanical loads, ship striking, mooring force and other external forces. In particular, ship striking may damage or break the pile, which will seriously affect the wharf safety. Therefore, in the design of the SHM system on the high-piled wharf, the main physical parameters are the structural displacement, pile stress, beam stress (track beam and cross beam), slab stress, inclination of piles, structural vibration, etc.

In general, a high-piled wharf is mostly built on soft foundation. Large deformation of the soft foundation can easily result in wharf structure inclining, component damaging and structure overturning, which will cause huge casualties and property losses. Therefore, the wharf displacement is an important parameter to monitor the health of a high-piled wharf. The health status of the plies, beams, slabs and other components can reflect the safety state of the wharf, so the strain of these key components can indicate the health conditions of the wharf to ensure operation safety on the wharf. Therefore, the strain of the key components of the wharf should be selected as important indicators for the wharf health-monitoring system. The damage and its position of structure can be determined by analyzing the variation in structural dynamic characteristics, which has been verified in many health-monitoring systems in high-rise buildings, large span bridges and other structures (Yi *et al*. 2013b). Therefore, the dynamic properties of the wharf structure should also be used as an indicator to monitor the long-term health. Meanwhile, the environment temperature should be monitored to correct the test results because of the temperature deformation of materials. In addition, the costal wharf works in seawater, and concrete crack and spalling occur because the reinforcement is corroded by chloride ions, which is notably different from the infrastructure on land. Thus, the corrosion potential of reinforced-concrete components should also be monitored in the SHM system.

3.1 Compositions of the SHM system

Generally, a structural health-monitoring system involves the sensor subsystem, data acquisition element, transmission and processing subsystem, data management subsystem, damage identification element, risk assessment and disaster-warning element. Based on the particular severing environment and monitoring parameters of the high-piled wharf structure, the health-monitoring systems of the South 27# Wharf structure are designed considering the feasibility of the monitoring system. The monitoring system is made up of a sensor subsystem, a data acquisition subsystem, a data transmission and storage subsystem, and a data processing and application subsystem, whose structure map is shown in Fig. 3.

This paper focuses on the sensor subsystem and the data collection and transmission parts. The key is to analyze the selection of sensor type and its use and to propose the data acquisition and transmission technology. Ultimately, the implementation specifications of a health-monitoring system for costal high-piled wharfs are provided.

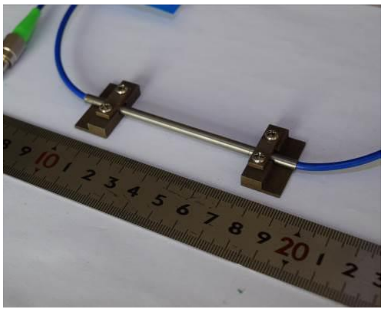
3.2 The use of hardware

The FBG sensor is the key element of the wharf health-monitoring system. Two data transmission methods are used: in site, FBG sensors are attached to the PC-based interrogator in the base station by the fiber, and the acquired data are transmitted via a wireless bridge to a remote control center from the base station. Because the vibration data can be used to detect damage to the wharf, the FBG acceleration sensor is used to measure the wharf vibration.

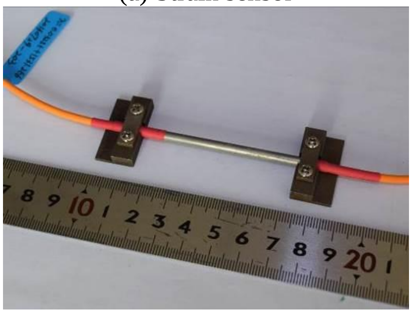
The anode ladders have also been installed on the reinforcement-concrete components to survey the corrosion potential of the steel bars.

3.2.1 FBG strain sensor and temperature sensor to monitor the strain and temperature

The FBG strain sensor and FBG temperature sensor were designed to monitor civil infrastructures by the Dalian University of Technology (Ren *et al*. 2004, Ren *et al*. 2014). The uniaxial FBG strain sensor has a range of ±1000 με, and the FBG temperature sensor has a range of -40~100℃, as shown in Fig. 4. The strain signals from the FBG strain sensors are digitized by the interrogator, which has a 32-channel programmable data collection software with user demand; the temperature signals are similarly digitized.



(a) Strain sensor



(b) Temperature sensor

Fig. 4 FBG strain and temperature sensors

3.2.2 FBG obliquity sensor to monitor the obliquity of the piles

The FBG obliquity sensor is used on the steel pylons to monitor its obliquity. This type of sensor is used to monitor the obliquity of wharf piles; it has a range of ±10° and a resolution of 0.1° as shown in Fig. 5.

Fig. 5 FBG obliquity sensor

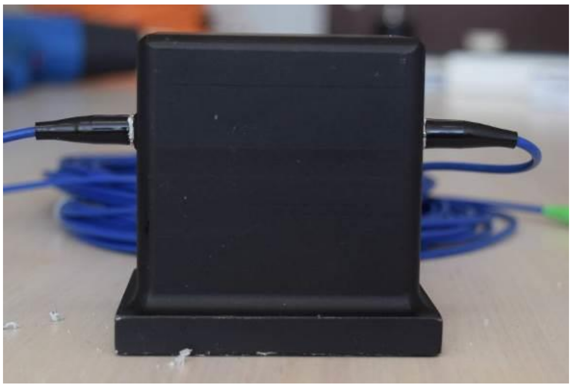


Fig. 6 FBG acceleration sensor

3.2.3 FBG acceleration sensor to monitor the wharf vibration

The FBG acceleration sensor is used to monitor the structural vibration of the South 27# Wharf, whose waterproof design can be better adapted to the marine environment. This type of sensor has a range of ±2 g and resolution of 0.02 g as shown in Fig. 6.

Fig. 7 Anode ladder sensor

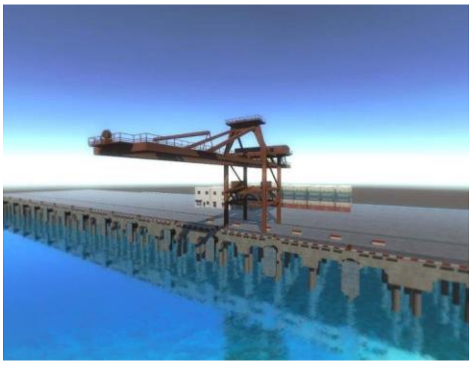


Fig. 8 3D model of the South 27# Wharf with BIM

3.2.4 Anode ladder sensor to monitor the corrosion potential of steel bars

The anode ladder sensor is designed to monitor the corrosion potential of steel bars in the reinforced-concrete components. It has been widely used for practical marine structures such as bridge spanning in the sea. Based on the monitored corrosion potential data, the remaining service life of the structure can be predicted. Thus, this type of sensor is selected to be set in the reinforced-concrete components of the South 27# Wharf to monitor the corrosion status of the steel bars in the reinforced-concrete components. Then, the remaining service life of the South 27# Wharf can be calculated. The anode ladder can also measure the electric current, concrete resistivity and concrete temperature, as shown in Fig. 7.

3.3 SHM system software

In principle, the performance of an SHM system heavily depends on the quality of management, display and processing of the health-monitoring data from the sensor network. To realize these functions, the SHM system software for the South 27# Wharf is customized based on the BIM (Building Information Model) technique. With this software, the monitored data can be stored, managed, displayed with the 3D walkthrough mode and processed with the integrated numerical algorithms in the software. In particular, the data display in the 3D mode with the BIM of the wharf is visual and original, which is the first time to be used in costal high-piled wharfs. The display interface is shown in Fig. 8. Based on the data processed, warnings about the structure risk can also be provided. This software implements key functionality to manage the high-quality sensor data in the base station via wireless communication from the sensor network and reliably process the data to access the health conditions of the wharf.

The sample rate is set to 50 Hz for the structural acceleration survey, so the data quantity of structural vibration is huge if acquired in real-time. Therefore, a threshold is set for the vibration measurement to reduce the power consumption and data amount. When the measured data exceeds the pre-defined threshold, the entire network for synchronized data measurement is weakened. In this method, the system enables the automatic, continuous monitoring with valid data.

In this deployment, an identical method is used to measure the ship impact force to the wharf. In conclusion, the final software can perform the automatic monitoring with applications in data measurement, management, processing and computational functionality. A multiple-threshold triggering strategy is also used to measure the structural vibration and ship impact force.

4. Deployment of the SHM system on the high-piled wharf

The hardware and software framework are currently deployed on the South 27# Wharf to establish the large-scale and autonomous system. Because of the harsh marine environment in site, FBG-based sensors are used in the SHM system to ensure its durability and prevent corrosion damage. Many measurements and verification steps have also been used to deploy the full-scale SHM for a costal high-piled wharf structure. Details of the sensor placement and setup in site are provided in this section.

4.1 Sensor network topology

The sensor network topology was carefully designed to ensure sensing for the South 27# Wharf reliably. The main factors that affect the sensor network topology design are the network size, distance between the sensor location and the base station in site, etc. The distance of the farthest sensor from the base station in site is 280 m, and this sensor can easily transfer data with the fiber. The number of sensors in the network is 424. Considering different sample rates, the sensor network was divided into two sub-networks: one for structural vibration survey and ship impact force measurement and the other for the remaining sensors.

The dynamic sub-network consists of 24 sensors with 8 acceleration sensors on the cross girders and 16 nodes on the berthing member of wharf. The remaining 400 sensors belong to the static sub-network. The two sub-networks are controlled by a high-frequency interrogator and a low-frequency interrogator, which are placed in a monitor room at the exit of the South 27# Wharf, where power can be permanently provided for the interrogators and other devices such as the wireless network bridge for data transmission.

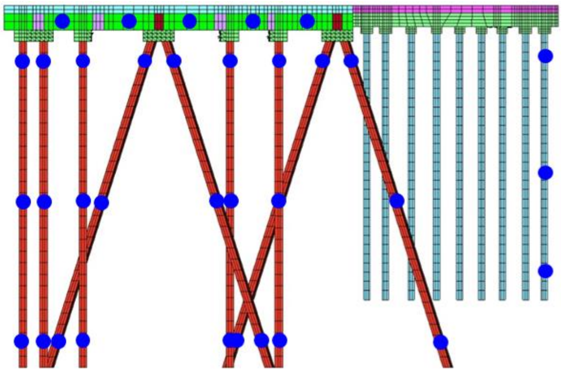


Fig. 9 Placement of the FBG strain sensors

4.2 Sensor deployed in site

Five types of sensors are used in the SHM system for the South 27# Wharf: the FBG strain sensor, FBG strain temperature sensor, FBG obliquity sensor, FBG acceleration sensor and Anode ladder sensor, which are developed and suitable for use in the marine environment. Many scholars have proposed several sensor placement optimization methods (Chow *et al*. 2011, Yi and Li 2012, Yi *et al*. 2015). Many methods are original, such as the immune monkey algorithm proposed by Yi *et al*. (Yi *et al*. 2015), which are effective and reliable on the sensor arrays of Canton Tower. Based on the practical condition of the wharf and many sensor placement optimization methods, the deployment and setup details of these types of sensors are described in this section.

4.2.1 FBG strain and temperature setup

In the SHM system for the South 27# Wharf, 289 FBG stain sensors are used to monitor the mechanical state of the prestressed reinforced-concrete cross girders, prestressed reinforced-concrete track beams, prestressed reinforced-concrete slabs, and prestressed reinforced-concrete piles and steel-pipe piles. The sensors are located at the midspan of each concrete component; three strain sensors are deployed at the top, middle and bottom parts of each pile, including the concrete and steel-pipe piles. The placement of these FBG strain sensors is shown in Fig. 9.

For the concrete components, the strain sensors are set up on the bottom steel bar of the components with the sensor supports, which are welded on the steel bar. Then, the concrete is poured, and the sensors are imbedded in the components. For example, the sensors in the prestressed reinforced-concrete piles are set up in the following steps. First, the fixed sensor on the steel support is set on the steel bar by welding; then, the fiber connected to the sensor is laid along the main steel bar with a colligation per meter by the tie wire. After completing the setup, the performance test of the sensors is performed with the mini interrogator. After the sensor is guaranteed to be in good condition, concrete is poured and vibrated. To protect the leading-out fiber from being broken, stainless-steel shells are used where the fiber protrudes from inside the pile. Finally, after the concrete curing is completed, the prestressed reinforced-concrete piles with FBG strain sensors and FBG obliquity sensor are shipped to construction site of the wharf and driven. Each step of setting these FBG strain sensors in the concrete piles is shown in Fig. 10.

The installation steps of the FBG strain sensors in the concrete cross girders, concrete track beams and concrete slabs are nearly identical to those of concrete piles. The main difference is the sensor location. Each concrete beam and slab have one FBG strain sensor in their midspan, whereas three FBG strain sensors are set in each concrete pile at its head, middle and end parts. The placement of the FBG strain sensors for the concrete cross girders, concrete track beams and concrete slabs is shown in Fig. 11.

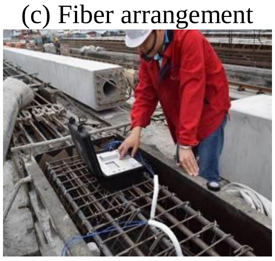
The most difficult task is to install the FBG strain sensor for the steel-pipe pile. Because the steel-pipe pile must be driven into the foundation under seawater, the sensor must be carefully protected and not broken by the hammering power and extrusion force of the soil. Thus, the strain sensors are set in the internal face of the steel pipe pile. To protect the sensors and to connect fiber to the sensors, a groove is made with angle irons by welding. Then, three FBG strain sensors are set up with equal distance along the groove at the top, middle and end parts of the pile.

(a) Sensors

(b) Sensor setup

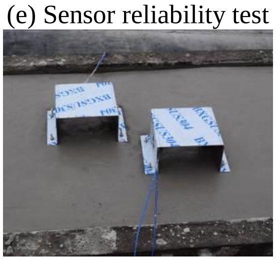
(c) Fiber arrangement

(d) Fiber colligation



(e) Sensor reliability test

(f) Concrete pouring



(g) Protection for leading-out

(h) Driving pile

Fig. 10 Steps of the FBG strain sensor setup for reinforced-concrete piles

(a) Sensor setup in the beam

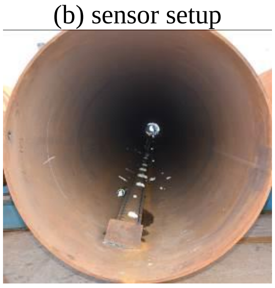
(b) Sensor setup in the slab

Fig. 11 Placement of the FBG strain sensors for concrete beams and slabs

(a) groove by welded

(b) sensor setup

(c) setup completed



(d) deck-plate welded

(e) leading-out terminal

Fig. 12Installation of the FBG strain sensors for the steel pipe

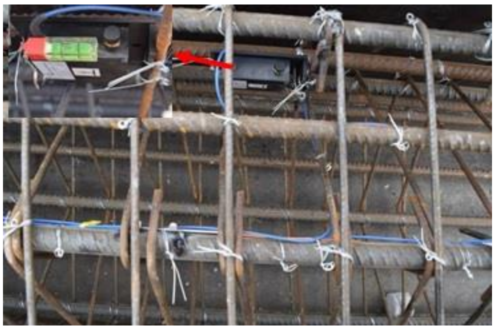
After the sensor setup, the groove is sealed with a steel deck-plate by welding. Then, the groove is filled with polyfoam to protect the sensors and the fiber from being broken by the hammering vibration. The sensor setup method is proven feasible in the pile-driving process, and the installation of FBG strain sensors for the steel-pipe piles is shown in Fig. 12.

4.2.2 FBG obliquity sensor setup

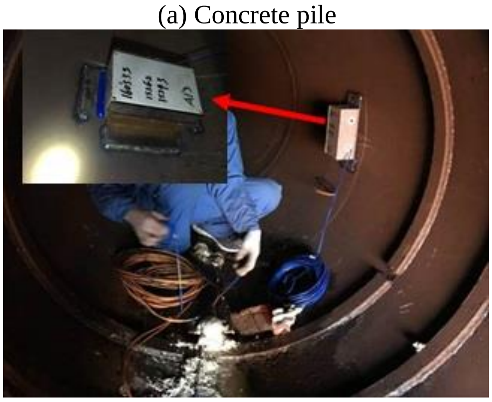
Generally, the transverse displacement of a high-piled wharf built on a soft soil foundation is the key indicator of the structural health condition. Thus, the structural transverse displacement should be monitored for an SHM system. However, because it is difficult to measure the transverse displacement of a high-piled wharf, the indirect method with the obliquity sensor is used to obtain the transverse displacement of a high-piled wharf. The dip angle of the pile can be measured by the obliquity sensor, and the transverse displacement of high-piled wharf can be calculated based on the dip angle of the pile and size of the wharf.

Therefore, the dip angle of the pile is selected as a monitoring indicator for the SHM system of the South 27# Wharf, and the FBG obliquity sensor is used because of the seawater environment. Nine prestressed reinforced-concrete piles in the back platform and fifty-seven steel pipe piles in the front platform are set for the FBG obliquity sensor, which is installed at the pile upside with a 1.0-m distance from the pile cap. The FBG obliquity sensor is set to measure the dip angle in the shoreside-to-apron direction.

The obliquity sensors are buried inside prestressed reinforced-concrete piles and installed on the inner face of the steel pipe piles, as shown in Fig. 13.



(a) Concrete pile



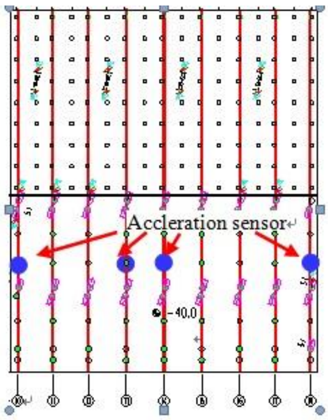
(b) Steel pile

Fig. 13 Installation of the FBG obliquity sensors for the pipes

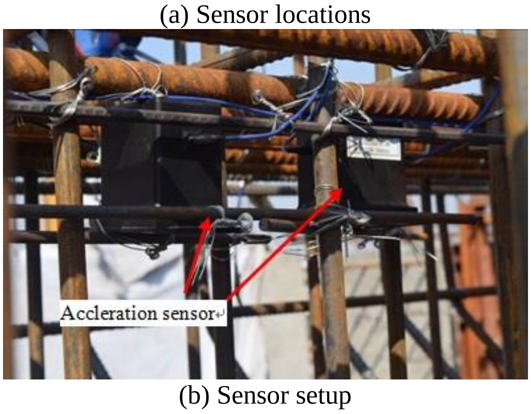
4.2.3 FBG acceleration sensor setup

Damage on the structure will affect and change the structural physical properties (mass, damping and stiffness). Thus, the structural damage can be detected with the measured structural-vibration data. Many structural-damage detection methods based on the measured vibration properties of structures have been proposed and proven effective by many tests (Li *et al*. 2004b, Yi *et al*. 2013). For example, the multi-stage structural damage diagnosis method based on the "energy-damage" theory was proposed by Yi *et al*. (Yi *et al*. 2013) and proven effective in structural damage detection with the ASCE benchmark structure. Therefore, the acceleration of the global structure is selected as a monitoring indicator for the SHM system of the South 27# Wharf. Based on the practical condition of the wharf, the FBG acceleration sensors are used to measure the acceleration of structural vibration.

The FBG acceleration sensors are designed to be installed at the middle area and both wings of the front platform at four locations (Fig. 14 (a)). At each location, the sensors are set up at the midspan of the cross girders to measure the structural vibration in the longitudinal and transverse directions. The acceleration sensors are buried in the concrete of the cross girders with a distance of 60 mm from the top surface. Then, the fiber connected to the sensor is led to the outside of the concrete along the vertical steel bar and lengthened to reach the interrogator in the monitor room on site. The sensors in the beam are shown in Fig. 14 (b).



(a) Sensor locations



(b) Sensor setup

Fig. 14 Installation of the FBG acceleration sensors

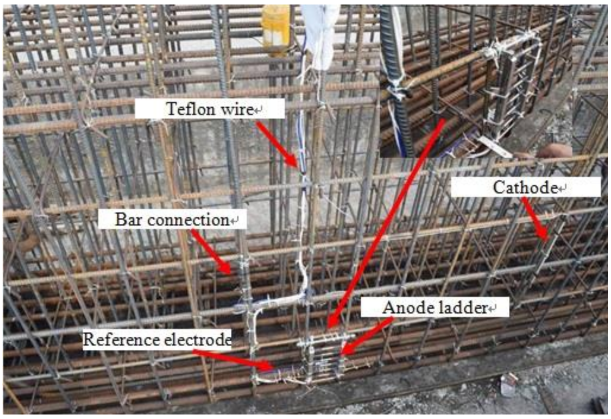


Fig. 15 The installation of the anode ladders

4.2.4 Anode ladder sensor setup

As previously mentioned, the service environment of a high-piled wharf is notably different from that of a civil engineering structure serving on land, where chloride ion erosion is an important cause of damage to coastal wharfs. Chloride ion erosion can cause the steel bar in the concrete to rust, and the rebar corrosion makes the rebar expand, which causes concrete cracking and spalling. Then, the concrete cracking accelerates the chloride ion erosion and further causes more serious steel-bar rusting and concrete damage. It is a vicious circle and seriously decreases the durability of reinforced-concrete components. Therefore, the condition of rebar rusting should be monitored in the SHM system for the South 27# Wharf.

In the NDT, the rebar corrosion status is often detected using the corrosion potential testing method. According to the measured corrosion potential between the steel bar and the concrete surface, the condition of the steel bar rusting can be determined. Thus, the anode ladder sensor is used to monitor the corrosion potential between the steel bar and the concrete surface. This sensor can measure the corrosion potential, corrosion current and concrete resistivity to more accurately monitor the corrosion condition of the steel bar. Therefore, four anode ladders are set at four locations: the cross girder of the back platform, cross girder of the front platform, track beam of the front platform and concrete slab of the front platform. The four anode ladders are all installed in the concrete cover of each reinforced-concrete component. The sensor locations are near the bottom surface of the components, where chloride ion erosion more seriously occurs to the concrete components because of the short distance to the seawater surface. The installed anode ladder in the cross girder is shown in Fig. 15. The installation method in the track beam and concrete slab is identical to that in the cross girder.

5. Conclusions

Currently, there are few studies on the health-monitoring technology of wharf structures in coastal ports. Based on the properties of high-piled wharfs in coastal ports and severe marine environment, a state-of-the-art SHM system using the FBG sensor technique is used for the South 27#

Wharf in the Tianjin port of China; the health-monitoring indicators and the sensors to measure these indicators are proposed. Until recently, all sensors have been set up in the prefabricated components, and the sensor network is being built. In the SHM system, the FBG sensors are used to measure the strain of reinforced-concrete beams and slabs, dip angle of the concrete piles and steel-pipe piles, environmental temperature and acceleration of structural vibration. In addition, the anode ladders are used to measure the corrosion potential between the steel bar and the concrete surface to monitor the durability of the wharf structure. The composition of the entire SHM system is devised to include a data transmission and storage subsystem, a data processing and application part and a data display part with the BIM technique.

In total, 289 FBG stain sensors, 87 FBG temperature sensors, 20 FBG obliquity sensors, 16 FBG pressure sensors, 8 FBG acceleration sensors and 4 anode ladders are installed in the components of the back platform and front platform. The components include reinforced-concrete beams and slabs, reinforced-concrete piles and steel pipe piles. All sensors in the concrete components are buried in the concrete, whereas the others are set in the groove welded by angle irons to protect them from destruction when the piles are driven. After the installation of some components in the wharf construction site, the good measured signal of each sensor demonstrates the suitability of the sensor setup methods and their suitability for the full-scale, continuous, autonomous SHM deployment for the high-piled wharf in the costal port. This study can provide a reference for the long-term health-monitoring system construction in coastal high-piled wharf structures, although many aspects should be studied more deeply on the health-monitoring technologies for coastal wharf structures.

Acknowledgments

This research work was jointly supported by the Natural Science Foundation of Tianjin (16JCYBJC21900) and the Fundamental Research Funds for Central Public Research Institutes (TKS140101, TKS150208). The authors would like to thank the Tianjin Research Institute for Water Transport Engineering, MOT and its financial support.

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