Research and Application of GPS in Bridge Structural Health Monitoring

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Abstract: As the number of bridges increases, the demand for bridge health monitoring is increasing year by year. With the progress of modern monitoring technology, the precision and efficiency of bridge monitoring have also been improved. There are many methods of bridge health monitoring with different characteristics, advantages, and disadvantages. However, with the development of information technology and satellite technology, Global Positioning System (GPS) monitoring appears to have more advantages, especially for the long-span Bridges. This paper mainly analyzes the components of GPS and the working principle of GPS monitoring. Meanwhile, it demonstrates that GPS monitoring methods have advantages of high frequency, all-weather and dynamic visualization of monitoring data by comparing with other monitoring methods. Finally, the paper analyzes the limitation of GPS monitoring and problems to be solved by a simple forecast of its future development.

1. Introduction

With the development of the economy, all kinds of large and complex projects have been gradually increased. People pay close attention to building safety problems in the process of operation, especially to the large bridge constructions which have been completed and put into use. The construction and operation safety issues should be focused on due to the complex structures for large bridges. In recent years the bridge deformation monitoring has become a hot spot. During the operation of the bridge, not only will it be influenced by natural factors, but also human factors, such as loads of passing vehicles. The structure may deform but should be kept within certain limits, also known as the bridge carrying capacity. Bridge deformation monitoring provides the most real and direct information in morph for bridge safety. At the same time, it provides basic data for bridge design and safety maintenance. Combined with Global Positioning System (GPS) technology which has been widely used, the establishment of the bridge monitoring system based on GPS is important.

Bridge deformation observation is an important branch of building deformation observation as well as the focus and hotspot of surveying and mapping engineering research. The geographical position of the bridge and its role in the life which determines the bridge deformation observation has its characteristics and decides the particularity of its deformation observation system. Too many enormous bridges have been built in recent years, however, due to a lack of sufficient deformation monitoring, building quality issues cannot be assured, and many large bridges around the world are in danger. In 1983, a highway bridge collapsed during operation in Connecticut, US, causing vehicles and people on the bridge to fall into the river. In October 1994, the deformed Seongsu Bridge in South Korea collapsed, killing 32 people and injuring 17 others. In August 2007, a large bridge over the Mississippi River collapsed in Minnesota, killing dozens of people [1]. After reviewing the significant bridge collapse accidents listed above, we may conclude that the following are the primary reasons for bridge collapse:

(1) During operation, the bridge is exposed to a variety of external variables, including strong winds, high temperatures, rain and snow, storms, weathering, and corrosion. As a result, the bridge's structural strength and rigidity are weakened until it can no longer hold the weight and collapses.

(2) The longer the moving load of vehicles on the bridge deck, the bigger the deformation of the bridge.

(3) Various unpredictable variables, such as the driving of large heavy vehicles, the inadvertent collision of ships and vehicles on the bridge columns or deck during the driving process, are unforeseeable and result in significant bridge deformation.

As a result, the bridge deformation monitoring work takes into account the bridge's normal functioning while also attempting to prevent all types of unexpected disasters and accidents, which is a critical task. In order to achieve real-time, dynamic, and accurate results, we should monitor the bridge body and the surrounding environment at each step of bridge construction, completion, and operation. And accurately control whether the bridge structure is normal, the bridge deck and underwater traffic conditions, and all other environmental factors that may affect the bridge structure and law. By combining examples discussed based on the establishment of a bridge deformation observation system based on GPS, the paper puts forward some opinions in the application process.

2. Application of gps in bridge structural health monitoring

At present, the construction speed of bridge projects is increasing, and many bridge project accidents are inevitably increasing, and the deformation monitoring of bridge structures is becoming more and more important. With the continuous progress of surveying and mapping instruments, new deformation monitoring methods are increasing, and GPS measurement technology is increasingly widely used in various fields of bridge engineering construction. The advantages of GPS measurement, which eliminates a large amount of intermediate measurement work in conventional measurement, provides efficient, fast, and high-quality measurement services for bridge deformation monitoring, and is more widely used in bridge engineering deformation observation.

2.1 Composition of GPS

The GPS is a satellite navigation and positioning system set up by the United States, enables users to achieve all-weather, continuous, real-time three-dimensional navigation and positioning and speed measurement worldwide. In addition, the system enables users to perform high-precision time transfer and high-precision precision positioning. The whole system of GPS is composed of space part, ground control part, and user part. The space component of GPS consists of 24 GPS working satellites, of which 21 are available for navigation and 3 are active-backup satellites. These 24 satellites are distributed in six orbits around the Earth with an inclination of 55°. The orbital period of the satellites is approximately 12 sidereal hours. Every working GPS satellite sends out navigation and positioning signals, and it is these signals that GPS users use to perform their work [2]. The control part of GPS consists of a monitoring system consisting of several tracking stations distributed around the world, which are divided into master, monitoring, and injection stations according to their roles. There is a main control station at Falcon Air Force Base in the USA. Its role is to calculate the ephemeris of the satellite and the correction parameters of the satellite clock based on the GPS observation data from the monitoring stations and inject these data into the satellite through the injection station; at the same time, it also controls the satellite, issues instructions to the satellite, and dispatches a backup satellite to replace the failed working satellite when the working satellite fails. The user part of GPS consists of a GPS receiver, data processing software, and corresponding user equipment such as computer meteorological instruments. Its role is to receive signals from GPS satellites and use these signals for navigation and positioning.

2.2 Principles of the Bridge Structural Health Monitoring by GPS

The GPS consists of different parts, each of them is following a certain principle. Above all, the GPS uses positioning methods to position the monitoring part. And then it will monitor certain deformation.

2.2.1 GPS Positioning Principle

The carrier signal, range code, data code, and other signal components can all be transmitted by a GPS satellite. At the same basic frequency, the carrier signal, range code, and data code are all regulated. Then the corresponding combination codes are then adjusted to an L1 carrier and L2 carrier frequencies via the navigation message to generate GPS signals.

The underlying principle of GPS positioning is space rear rendezvous. GPS satellite position is provided in real-time by navigation message, which is a known point of spatial dynamics. The basic observation quantity is the spatial distance between a GPS satellite and a receiving antenna, which can be calculated using the satellite's instantaneous coordinates and the spatial distance between satellite and receiving antenna to obtain the three-dimensional coordinates received by users.

For pseudo distance measuring, GPS primarily employs rangefinder code. Rangefinder code, on the other hand, cannot match the requirements of high precision in some applications due to its long code length.

2.2.2 GPS Monitoring Principles

The primary functions of a GPS monitoring system are to monitor the bridge's spatial displacement in real-time, determine the bridge's deformation, provide data to verify whether the bridge structure is safe, and promote the study of the relationship between bridge displacement and the environment (such as wind, temperature, and other factors). The design of a monitoring system must take into account a wide range of parameters and generally adhere to the four main principles listed below.

(1) Reliability: The data collected by the system must be accurate and reliable, and can correctly reflect the changes of each engineering building in different periods to achieve stable and reliable results. And the failure rate should be relatively low, once the emergency can also be a timely response.

(2) Advancement: Due to the fast acquisition speed and high precision of bridge engineering deformation monitoring data, dependable and advanced observation equipment must be prepared. To accomplish high-precision autonomous observation and better data processing, the data processing method should also be upgraded.

(3) Economy: The system should operate safely and reliably, meet the accuracy criteria of deformation analysis and the density requirements of monitoring points. Also, the system's optimization effect should be taken into account. Choose a suitable and reasonable operation mode; point layouts should be few and exact; prices should be kept as low as feasible, and excessive waste should be avoided.

(4) Comprehensiveness: Bridge engineering is a relatively complex system engineering, the monitoring system should be integrated the use of GPS technology, computer technology, modern sensor technology, structural analysis, and other methods to establish a comprehensive safety monitoring system with complete functions and superior performance, including displacement monitoring, structural stress monitoring, environmental monitoring and so on.

2.2.3 GPS Positioning Methods

The GPS positioning technology is highly precise, dynamic, automatic, and can operate under almost any circumstances. It will inevitably become more widely used in deformation monitoring, particularly for large projects. Periodic monitoring, as one of the most often used methods, can be divided into static measurement, fast static measurement, and dynamic measurement methods, depending on the monitoring objects and requirements.

(1) Static measurement: Place over 3 GPS receivers on the observation point. Synchronous observation is performed over some time, usually one or two hours. The static measurement approach

typically employs a long edge with excellent positioning accuracy, relative edge measurement accuracy can be up to 10^{-9}.

(2) fast static measurement: It is especially useful in observation at monitoring sites. At the reference position, two GPS receivers are installed, and fixed and continuous observations are taken. The sampling interval was set at two seconds, and each observation period was set at five to ten minutes. The post-processing software is used to analyze and settle accounts based on the gathered observation data of monitoring points, and the real-time 3D coordinates of each monitoring point are obtained.

(3) dynamic measurement methods: This method is split into two categories: quasi-dynamic measurement and real-time dynamic measurement. The RTK method, a real-time differential GPS measuring methodology based on carrier phase observation, is a real-time dynamic measurement approach. The premise of RTK is to use a GPS receiver at the reference station to constantly observe all visible GPS satellites and communicate the observation data to the GPS receiver moving observation at each monitoring point in real-time via radio transmission equipment. When receiving GPS satellite signals, the receiver also receives the radio equipment's reference observation data, which is then used to calculate the 3D coordinates and accuracy of each monitoring point in real-time using the differential positioning principle, with a general accuracy of up to 2~5cm. At the reference point and monitoring point, there are more than 5 common GPS satellites, and their precision can reach 1~2cm.

2.3 Content Detected by GPS Monitoring

The monitoring of bridge deformation mainly includes horizontal displacement monitoring, vertical displacement monitoring, deflection monitoring, tilt monitoring, and crack monitoring. The purpose of horizontal displacement monitoring is to track the movement of a deformed body in the horizontal plane over time. Typically, we describe the plane coordinates across time, compare the plane coordinates before and after the change, and calculate the distance and direction of deformation. The methods mainly used are the datum line method and traverse method. Vertical displacement observation is mainly used to observe the deformation of deformed bodies in the vertical direction, also known as subsidence observation or settlement observation. Its primary manifestation is the change in elevation over time. During the bridge's operation, the measurement point is frequently examined using a precise leveling method to estimate its elevation, and the elevation change over time is calculated by comparing the elevation of the same measurement site over time. The results of the evolution of horizontal displacement and vertical displacement are deflection monitoring, tilt monitoring, and crack monitoring, which are the synthesis of horizontal displacement and vertical displacement, which can be expressed by horizontal displacement and vertical displacement.

GPS monitoring system through the sensor of each measurement point of the three-dimensional vector real-time monitoring and the bridge deck, the bridge tower on the GPS receiver will each receive information through the fiber optic cable to the central master computer. This allows the bridge position to be indicated under an error of less than 2 cm. The GPS monitoring system can also calculate the wind and wind speed of the surrounding environment to help estimate the stress and load conditions of the bridge structure. GPS monitoring of bridge piers mainly includes horizontal displacement monitoring and vertical displacement monitoring. The horizontal displacement monitoring includes both horizontal and vertical monitoring, and vertical monitoring refers to the horizontal displacement monitoring of each bridge pier and abutment along the bridge axis direction. Different bridges can choose different horizontal displacement measurement methods, such as angle measurement method, baseline method.

Vertical displacement monitoring of piers is to regularly measure the monitoring points distributed on the piers, analyze and process the elevation change and deformation data, and complete the analysis of the vertical displacement law of piers. It mainly includes the observation of vertical displacement at the characteristic position of piers and the observation of tilt in the direction perpendicular to the axis of the bridge. The current method of bridge vertical displacement monitoring is mainly precision level measurement and triangle elevation measurement.

The monitoring content of the bridge plane is mainly the horizontal displacement monitoring perpendicular to the direction of the bridge axis. Due to external factors such as vehicle load, wind load, and other external factors, the bridge foundation displacement deformation. Such as cable-stayed bridges, suspension bridges, and other bridges with large spans, wind loads have a more obvious effect on them, so the use of GPS can carry out better monitoring and solve the influence of the bridge structure on the results. GPS monitoring of bridge deck deflection refers to the magnitude of vertical displacement of the bridge deck along the bridge axis. The deformation of the bridge deck due to external factors makes the design shape of the bridge different from the actual shape, and GPS is efficient and easy to measure the deflection of the bridge.

In addition, GPS monitoring can be used to evaluate the structural health of the bridge. GPS measures the instantaneous displacement of the bridge body and projects the displacement of its cross-sectional axis position to evaluate the stress condition of each corresponding major component. It first collects the displacement of the bridge structure as a whole to infer its surrounding environment and load changes. It then calculates and analyze the stresses of the main members and verifies unusual load records and special time alarms, such as typhoons, earthquakes, car accidents, etc. By analyzing the structural forces of the bridge, it can deduce the damage to the bridge.

The frequent observation, high observation precision requirement, broad application of diverse observation methods, rigorous data processing method, and multi-disciplinary cooperation are all hallmarks of bridge deformation observation. Because deformation occurs continuously, we must conduct periodically repeated observations of the bridge, the length of which is determined by the magnitude and speed of deformation as well as the aim of the observation. Using GPS and other sensor combination technology will become an inevitable trend. Firstly, GPS technology combined with plane survey and elevation survey can realize synchronous observation of vertical displacement, horizontal displacement, and deflection of engineering. Secondly, GPS measurement has the advantages of high precision, all-weather, real-time dynamic, and enough to provide the position or movement information of the bridge monitoring point relative to an absolute reference system in a certain period. Compared with traditional measurement methods, its advantages are incomparable.

2.4 Advantages of GPS monitoring

By comparing GPS monitoring with other common bridge health monitoring methods, the advantages of GPS monitoring are analyzed in detail, as shown in Table 1.

2.4.1 Common Monitoring Methods

Common monitoring methods includes geodetic method, physical sensor method, photographic method, interferometric synthetic aperture radar method and 3D laser scan method.

(1) Geodetic Method

By electronic or optical measuring instruments, measuring Angle and distance with to obtain the vertical displacement and horizontal displacement of the bridge structure. This method has simple operation, high flexibility, and high accuracy. With the emergence of various precision instruments, geodetic methods have been widely used in bridge monitoring, which can meet the accuracy requirements of bridge deformation with different structural forms. However, in practical application, the monitoring speed of this method is slow, the degree of automation is low, and the monitoring range is limited. Moreover, it needs to invest a lot of manpower and material resources and it is easy to be affected by the site topography, weather, and visibility conditions. Finally, it is impossible to measure the local deformation of the bridge.

Table 1. Comparison of different sensors.

Method	Advantages	Disadvantages
Geodetic method	Simple operation High flexibility High precision Suitable for different structural of Bridges	Slow monitoring speed Low degree of automation Limited range High cost Susceptible to topography and weather Don't measure the local deformation of the bridge
Physical sensor method	Flexible use Long-term observation Less environmental impact The high degree of automation	Don't measure the overall deformation of the bridge
Photographic method	Small fieldwork No topography restrictions Fast access to bridge information Reliable Suitable for large-scale monitoring	Low precision High cost of measuring equipment
InSAR method	Penetrable Weather-free Ultra-high precision Fast access to bridge information	Expensive Don't access target information directly
3D laser scan method	Fast scanning speed High precision Real-time Initiative The outcome can be directly applied to other tools	Difficult to test Expensive equipment Complex data processing Poor compatibility of equipment
GPS method	High precision No topography and weather restrictions The high degree of automation Less fieldwork Suitable for large-scale monitoring	Low vertical displacement monitoring precision High cost

(2) Physical Sensor Method

Physical sensors are used to obtain information on stress, pressure, tilt Angle, temperature change, and local deformation. The physical sensor is fixed in the bridge and is flexible in use. It can observe continuously for a long time and realize automatic observation in any environment. However, this method can only monitor the local and relative deformation of the bridge and cannot monitor the overall deformation of the bridge.

(3) Photographic Method

To obtain the geometric and physical information of the bridge, an optical camera is used to capture the image and reconstruct the spatial geometry and physical model of the target. This method has small fieldwork and is not limited by natural geographical conditions. It can quickly obtain bridge information without contact, avoiding the cumbersome steps of field acquisition, and provide three-dimensional spatial coordinates for static targets and the change law of dynamic targets, which is suitable for large-scale ground deformation monitoring, However, the accuracy of this method is not very high, and the cost of measuring equipment is high.

(4) Interferometric Synthetic Aperture Radar (InSAR) Method

According to the phase data of radar image, obtaining high precision and high-resolution ground elevation information. InSAR has the characteristics of penetration ability, not affected by cloud and rain weather and all-weather monitoring. The accuracy can reach centimeter-level or even millimeter-level. It can obtain the static and dynamic deflection changes of the bridge in a short time, with a maximum natural vibration frequency of 200 HZ, static accuracy of 0.1mm, and dynamic accuracy of 0.01mm. Meanwhile, combined with the corner reflector, this method can obtain micro deformation at any position of the pier. However, it is expensive and cannot directly obtain the three-dimensional information of the target, which needs to be obtained by projection.

(5) 3D Laser Scan Method

Through the instrument scanning of the surface of the object intensively, a large number of high-precision point cloud data of the object can be obtained, and any object can be scanned without the limitation of day and night. Hence, the entity target can be quickly converted into processable data. This method plays a more and more important role in the field of bridge monitoring because of its fast-scanning speed, high precision, strong real-time, strong initiative, and output format, which can be directly applied to CAD, 3D animation, and other tools software. However, it is difficult to check, the instrument is expensive, and the data post-processing is complex.

2.4.2 The Advantages of GPS Method

By using GPS monitoring method, the precision can reach millimeter level, but in the vertical direction, the displacement precision is lower. Generally, its precision is higher than the Photographic method, InSAR method, and 3D laser scan method, but lower than the Geodetic method. In the environment, unlike Geodetic Method influenced by the terrain and the weather, the Photographic Method is influenced by the weather, GPS is not influenced by topography, weather, and distance. GPS receiver can receive working satellite signals at any time, and it’s easy to achieve long-term continuous monitoring in bad weather such as snow, rain, and fog. In degree of automation, compared with the Geodetic method requiring a large amount of manpower, GPS requires less fieldwork, which reduces the impact of human factors on monitoring and has a high degree of automation. In speed acquiring information, at present, the sampling rate of the GPS receiver has reached 20 Hz or even 100 Hz, which means GPS cannot only measure 3D displacement with high precision but also obtain time information with precision up to 30 ns. Hence, compared with the Geodetic method, GPS can obtain more data. In deformation monitoring of large Bridges, compared with other methods, GPS has advantages in monitoring due to the wide perspective of satellites, although more receivers will increase the cost.

3. Conclusion

According to the composition of the GPS that was composed of space part, ground control part and user part and its application in Bridges, mainly in health monitoring, this paper analyzes its monitoring principle, monitoring methods, and monitoring content. For safety, it is necessary to monitor the deformation of the pier, tower column, bridge deck deflection, and the horizontal displacement of the bridge deck. Finally, the paper compares GPS monitoring with other monitoring methods. Based on the comparison, the analysis leads to the main following findings: high precision, no topography and weather restrictions, high degree of automation, less fieldwork, and suitable for large-scale monitoring.

Although GPS monitoring has huge advantages, it still has many limitations. For some Bridges, if there is a shield between the monitoring point and the satellite resulting in a bad field of vision, the accuracy will be affected. Meanwhile, due to more monitoring points, the GPS method will cause higher costs. In addition, due to the high price of GPS receivers, large-scale popularization and application are limited. Compared with the Geodetic method, the accuracy of measurement needs to be further improved. Finally, the software processing system suitable for GPS monitoring is not perfect currently and the whole processing system needs to be strengthened.

For promoting the application of GPS in bridge health monitoring, starting from more kinds of sensors is necessary. Usually, to reduce the monitoring cost, GPS monitoring systems don't adopt real-time kinematic receivers, because it has disadvantages that it needs to process GPS signals separately with precision calculation software and real-time monitoring cannot be realized. Therefore, the establishment of real-time GPS wireless network transmission and automatic computing platforms can effectively solve this problem. Meanwhile, due to the high cost of the receiver, the development of an inexpensive receiver can also promote the development of GPS monitoring.

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